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Handbook for the Assessment and Management of Magnetic Fields Caused by Distribution Lines

Prepared by
Enertech Consultants
Lee, Massachusetts

R E P O R T   S U M M A R Y

Handbook for the Assessment and Management of Magnetic Fields Caused by Distribution Lines

Distribution lines constitute one of the major sources of the public's time-weighted average exposure to magnetic fields. This report discusses the three main sources of magnetic fields along with statistically significant data for each source, methods of calculating distribution line magnetic fields, and general guidelines for performing distribution line magnetic field measurements. Technologies for magnetic field exposure reduction are presented and discussed, with emphasis on the most promising techniques.

INTEREST CATEGORIES

Electric and magnetic fields
Overhead planning, analysis, and design

KEYWORDS

Distribution lines
Transmission lines
Magnetic fields
Shielding

BACKGROUND The general public has become increasingly aware of possible health effects from exposure to electric and magnetic fields (EMF). This has led to controversy, delay, and cost increases in the construction of some utility lines and facilities. EPRI has initiated research to identify field sources, characterize field levels, and provide management options and strategies that could be used to reduce fields and exposures.

OBJECTIVE To provide data on typical distribution system current levels, magnetic field levels near the lines, residential exposures to the public, and magnetic field management options.

APPROACH Investigators gathered available data on representative current and magnetic field levels. Using a set of simplified expressions for calculating distribution line magnetic fields, they identified the principal parameters governing magnetic field levels and the optimal strategy for magnetic field exposure reduction.

RESULTS This report provides utility engineers with insight into representative data on magnetic field levels inside residences and in proximity to distribution lines. Typical current levels (average current, current unbalance, and net current) of three-phase distribution lines in the United States are provided for both the fundamental (60 Hz) and harmonic frequencies. The report describes commonly used methods for calculating distribution line magnetic fields based on typical current levels. In addition, it offers guidelines for performing distribution line magnetic field measurements, including spot measurements, lateral profiles, and temporal variations. Finally, it identifies options for managing magnetic fields from distribution lines. Following are the most promising field reduction strategies:

- Balanced primary lines can be reduced by compacting the phase conductors, reducing the line current by increasing voltage, or increasing the distance to the subject by relocating the line or raising the conductors.
- Net current primary line magnetic fields can be reduced by balancing the phase currents, increasing the size of the neutral conductor, isolating the primary and secondary neutrals, or implementing a five-wire system.
- Secondary line magnetic fields can be reduced by using triplex cable in lieu of an open-wire secondary configuration.

• Residential grounding system magnetic fields can be reduced by properly locating the distribution transformer, repairing broken service neutrals, or inserting a net current control device on the service drop.

EPRI PERSPECTIVE EPRI's goal is to provide tools, concepts, and guidelines for reducing magnetic fields from distribution lines. Magnetic field characterization and management for distribution lines is more complicated than for transmission lines due to the inherent variability of loads and the relatively high proportion of unbalanced current and harmonic content. Complicating the issue further, distribution lines have gone through a tremendous evolution over the past several decades, yet many of the older distribution line designs are still in operation. While wholesale changes in the design of existing distribution lines may not be practical or necessary, construction of new overhead lines with balanced loads may reduce losses, enhance system protection, and result in low magnetic fields.

PROJECT

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ABSTRACT

Distribution line magnetic fields are determined by the geometrical characteristics and currents of the conductors that form the distribution line, plus, in some cases, the geometry and currents of other conductors carrying some portion of the distribution line ground return current. This report provides utility engineers with insight into representative data on magnetic field levels inside residences and in proximity to distribution lines. Typical current levels (average current, current unbalance, and net current) of three-phase distribution lines in the United States are provided for both the fundamental (60 Hz) and harmonic frequencies. The report describes commonly used methods for calculating distribution line magnetic fields based on typical current levels. In addition, it offers guidelines for performing distribution line magnetic field measurements, including spot measurements, lateral profiles, and temporal variations. Finally, it identifies the most promising options for managing magnetic fields from distribution lines.

ACKNOWLEDGMENTS

The authors would like to thank Ashok Sundaram, EPRI Project Manager of the Custom Power Distribution Program, who directed the development of the Distribution Power Quality Node Database.

The contribution of the personnel of EPRI Power Delivery Center at Lenox, Massachusettes in the execution of laboratory tests of ground current reduction techniques is gratefully acknowledged.

The authors are also indebted to the countless hours spent by Marie Silva to extract and assemble key parameters from the Power Quality Node database.

CONTENTS

SECTION **PAGE**

LIST OF FIGURES

Figure PAGE

Figure **PAGE**

1

INTRODUCTION

1.1 Background and Objectives

As research into possible health effects from electric and magnetic field (EMF) exposure continues, utilities and others need to characterize field sources and field levels, and to provide management options to reduce fields and exposures. EPRI research on magnetic field management has resulted in a series of publications [1-4], addressing magnetic fields of transmission lines and other sources; low field designs, shielding methods, and cancellation loops. This publication extends the series to cover the subject of magnetic fields from distribution lines.

Magnetic fields from distribution lines have been studied extensively by EPRI, individual electric utilities, and other organizations. Distribution lines are widespread and constitute one of the preeminent electrical facilities in the eyes of the public. Furthermore, proximity to distribution lines has been associated with the risk of childhood cancer in three epidemiological studies [5-7]. EPRI has recognized the importance of collecting and summarizing the available information on distribution line magnetic field, magnetic field exposure, and magnetic field management options. This report discusses methods of measurements, calculations, and exposure assessments. Technologies for magnetic field exposure reduction are presented and discussed. This report, however, is not a handbook of magnetic field management options. A complete assessment of magnetic field management is not available because many of the technologies have not been fully developed or adequately demonstrated.

This report is intended for utility engineers who need to assess the contribution of distribution lines to EMF exposure and need to know which field reduction techniques are most promising. This report is also intended to help epidemiologists with planning and interpretation of epidemiological studies, decision makers in and outside electric utilities with information on how to allocate resources to EMF exposure reduction, and regulators and organizations charged with assessing the risk associated with the contribution of distribution lines to EMF.

The report consists of the following sections:

<u>Section 1</u> describes the objectives of the report and the fundamental characteristics of magnetic fields produced by electric power distribution lines.

Section 2 reports representative data on magnetic fields produced by distribution lines in the United States. Both field values inside residences and directly underneath (or directly above for underground cable) distribution lines. These data were obtained during EPRI's 1000-home residential magnetic field survey.

Section 3 reports representative data on the levels of average current, current unbalance, and net current in three-phase distribution lines in the United States. These data were obtained from EPRI Power Quality Nodes installed on randomly selected 3-phase distribution line feeders.

Section 4 describes commonly used methods for calculating distribution line magnetic fields, discusses the effect of unbalance and net current, and presents a simple method to estimate magnetic field given the average current, unbalance, and net current.

Section 5 presents general guidelines for distribution line magnetic field measurements, including spot measurements, lateral profiles, and temporal variations.

Section 6 describes a number of techniques for distribution line magnetic field reduction.

The report has two appendices. Appendix A describes RESICALC, the EPRI software program recommended for the calculation of magnetic fields from distribution lines. Appendix B describes EPRI's Magnetic Field Research Facility at the Power Delivery Center in Lenox, Massachusetts, which was built specifically for studies of distribution line magnetic field characterization and reduction.

1.2 Distribution Line Characteristics Affecting Magnetic Field

The magnetic field of distribution lines is determined by the geometrical characteristics and currents of the conductors that form the distribution line, plus, in some cases, the geometry and currents of other conductors that carry some portion of the distribution line ground return current. The most common overhead distribution line types and their characteristics affecting magnetic field are shown in the following:

3 Wire, 3-phase primary (delta or ungrounded wye)

The three phase, three wire primary shown in Figure 1-1 generally supplies residential customers through distribution transformers whose primary winding is connected between two phases of the 3-phase primary. There is no need for a primary neutral wire. The currents in the three wires may differ in magnitude and their phase angles may not be exactly 120 degrees apart from each other. However, the vectorial sum of the three currents is zero, i.e. there is no net current.

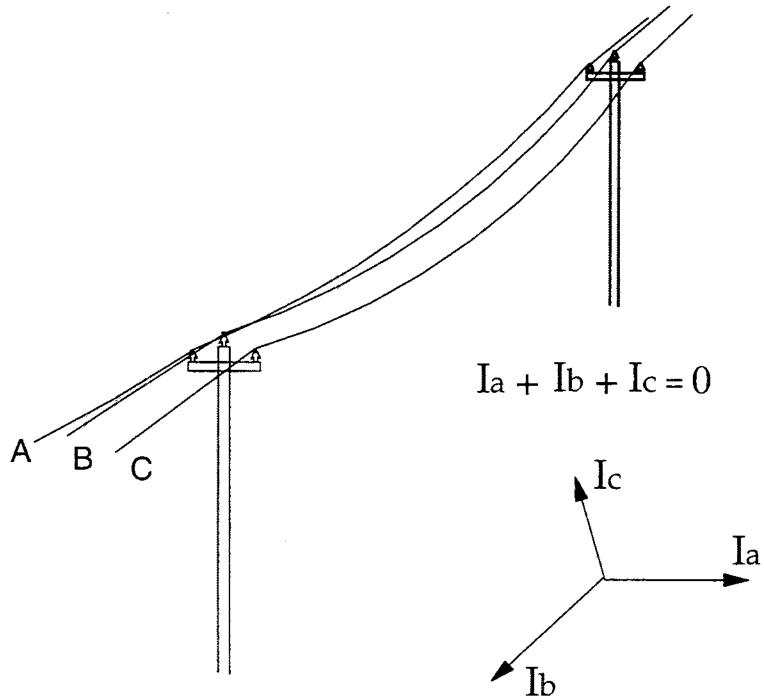

Figure 1-1 Three phase three wire distribution primary

4 Wire, 3-phase primary (grounded wye)

The three phase, four wire primary shown in Figure 1-2 typically supplies loads that are connected phase-ground so the three current phase angles are close to 120° apart from each other. However if there is any unbalance between the phase currents this type of system produces a net current which can flow in the system neutral and in the earth through the grounding system.

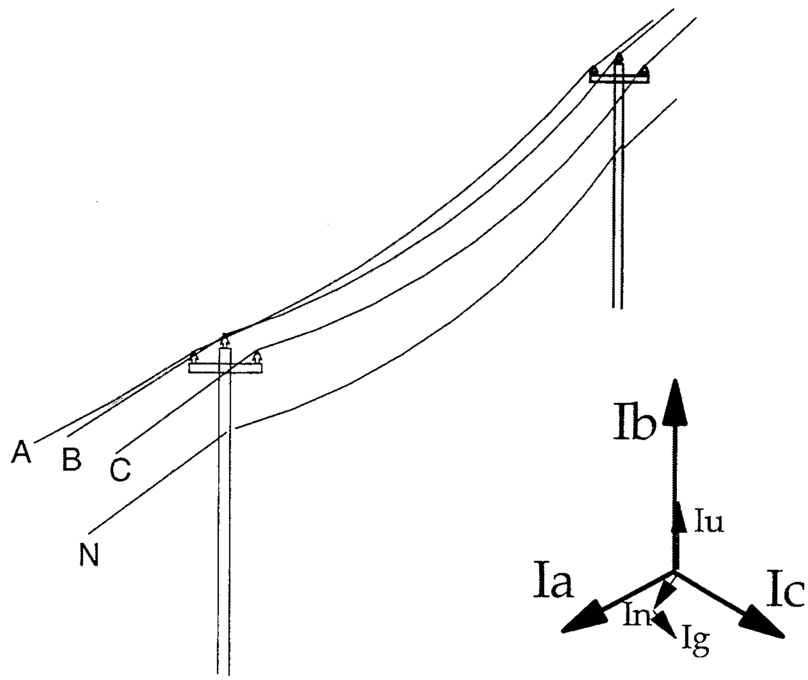

Figure 1-2 Three phase four wire distribution primary

1.3 Wire Codes

The basic rules to determine the "wire coding" of a residence were first developed by Wertheimer and Leeper[7]. These rules were subsequently modified[8,9]. Five categories of wire codes are commonly used as shown in Table 1-1 and listed below:

<u>Wire Code Configurations</u>

Wiring Classifications:

(The difference between thick and thin wires was left to the judgement of the wire coder)
Class 1. Thick, three-phase primary lines, transmission lines, or six or more non grounded wires
Class 2. Thin, 3-phase primary lines
Class 3. Long, first span secondary lines
Class 4. Second-span secondary lines
Class 5. Short, first span secondary lines

Class 6. End-pole situations
Class 7. Underground lines

Wire Code Classifications:

VHCC (Very High Current Configuration)
Class 1 within 50 feet (15 meters)
Class 2 within 25 feet (7.5 meters)

OHCC (Ordinary High Current Configuration)
Class 1 between 50 and 129 feet (15 to 39.5 meters)
Class 2 between 25 and 64 feet (7.5 to 19.5 meters)
Class 3 within 50 feet (15 meters)

OLCC (Ordinary Low Current Configuration)
Class 1 between 130 and 150 feet (40 to 46 meters)
Class 2 between 65 and 150 feet (20 to 46 meters)
Class 3 between 51 and 150 feet (15.5 to 46 meters)
Class 4 within 150 feet (46 meters)
Class 5 within 150 feet (46 meters)

VLCC (Very Low Current Configuration)
Class 6 - Class 3, 4, or 5 where there is no downstream service drops and there is break in the secondary downstream.

Underground (UG) - All distribution and transmission lines underground within 150 feet (46 m)

The 1000-home study has determined the following estimate of the proportion of each wire code among the overall population of US residences:

Table 1-1
Wire Code Categories

WIRE CODE	**Proportion of Residences (%)**						
	Transmission Lines	Thick 3-Phase Primary	Thin 3-Phase Primary	Six or more non-grounded wires	First span secondary	Other	**Total**
Very High Current Configuration (VHCC)	0.5	6.5	1.0	0.6			**8.6**
Ordinary High Current Configuration (OHCC)	0.6	7.9	2.4	1.0	7.4	0.2	**19.5**
Ordinary Low Current Configuration (OLCC)			2.1		7.5	12.5	**22.1**
Very Low Current Configuration (OLCC)						26.6	**26.6**
Underground Distribution (UG)						23.2	**23.2**

1.4 References

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2

DISTRIBUTION LINE MAGNETIC FIELD DATA

2.1 Introduction

Distribution lines may generate magnetic fields in three regions of interest: inside residences, in the immediate proximity of the lines where there is public access, and in the proximity of the conductors where workers are exposed. The fields inside residences are of special interest because they have the greatest impact on total human exposure. The fields near the lines in public access areas are of interest because they generally represent the highest field from distribution lines that the public can experience. The fields near the conductors are those to which utility workers may be exposed during maintenance work.

Distribution line fields have been extensively measured. The most systematic data are found in the Database of the EPRI 1000 home study [1]. These data are a representative sample that describes the field levels that exists near distribution lines in the United States.

2.2 One Thousand Home Study Database

The Electric Power Research Institute conducted a nationwide survey to collect engineering data on the sources of power frequency magnetic fields that exist in residences. Approximately 1000 residences were randomly selected for the survey. Reference (1) describes the results obtained from the survey, the measurement protocol, measuring techniques and the methods of data analysis.

The goals of the residential survey were: 1) to identify all significant sources of 60 Hz magnetic field in residences, 2) to estimate for each source the percentage of residences where magnetic fields exceed specified levels, 3) to determine the relationship between magnetic field and source parameters, and 4) to characterize the field variations in space and time. The survey has provided a significant pool of engineering and scientific data for the utility industry that is used for analytical studies, predictive techniques and field management studies.

Special techniques were used to determine how the magnetic field varied within the living space of the house (spatially) and over a 24-hour period (temporally). The field from each source is expressed in terms of how frequently a given field level was exceeded.

The residential survey identified the following sources of residential magnetic fields:

- Electrical appliances
- Grounding system of the residence
- Overhead power distribution lines
- Overhead power transmission lines
- Underground power transmission lines
- Ground connections at electrical subpanels
- Electrical wires used for ceiling or floor "radiant" heating
- Electrical wiring associated with some multiple-way switches
- Knob and tube wiring (old type of wiring where the wires are separated by a few inches)

The most common sources of residential 60 Hz magnetic fields were electrical appliances, the grounding system of the residences, and power lines.

The largest magnetic fields are produced by electrical appliances. However, fields decrease rapidly with the distance from appliances.

Power lines include both transmission lines and distribution lines. However, transmission lines were a contributor to residential fields in only 2% of the residences. Distribution lines, on the other hand, were a contributor to residential magnetic fields in most of the residences surveyed.

Power lines generally produce the largest average residential field. The average field data refer to a spatial-temporal average that includes the entire living space of the residence and a 24 hour period. Power line average residential fields exceeds 1 mG in 17.0% the residences, with a 95% Confidence Interval (CI) from 13.4% to 20.7%. Power line average residential field exceeds 2.5 mG in 3.3% of the residences (CI = 1.7%-5%), and exceeds 5 mG in 0.3% of the residences (CI = 0.1%-0.6%).

Power line fields were separated into: balanced field (i.e. field caused by the line currents, assumed balanced, see Section 4), and ground field (i.e. field caused by the net current of the distribution line, which returns to the transformers through the ground or other ground potential paths, see Section 4). The ground field component of the distribution line field is widespread. However the balanced component is more significant when average distribution line residential field exceeds 1.6 mG. This situation occurs for about 4% of the residences.

The 1000 home study produced a comprehensive database that contains as many as 1455 variables for each of the 1000 residences. These variables include distribution line data of interest, such as:

- Electrical parameters of the residential service

- Data describing the distribution secondary
- Electrical and geometrical characteristics of each distribution line adjacent to the residence
- Residence wire code
- Data describing the temporal variations and statistics of distribution line fields measured inside the residence
- Data on third harmonic and total harmonic distortion and their temporal variations
- Data on magnetic fields at different distances from the line, from the closest point to points past the residence

The Database is available from EPRI in various formats. It has been used to produce the tables and graphs presented in the next part of this Section.

2.3 Types of Distribution Lines Found in the 1000 Home Study

Currents in overhead power distribution lines adjacent to residences are a source of residential magnetic field. The magnetic field at the residence is a function of current and position of each wire. There are many different types of overhead power distribution lines, each characterized by the number of primary and secondary circuits, their voltages, number of wires comprising each circuit, their connection to distribution transformers, and relative position of each wire with respect to the center of the line.

Different types of overhead lines were defined for the purpose of the residential survey. They are listed in Table 2-1.

Table 2-1
Types of Distribution Lines

Line Type	Description	Number of Residences
Type 0	Underground distribution	243
Type 1	Secondary only	70
Type 3	1-Phase primary and neutral, no secondary	119
Type 4	2-Phase primary, no secondary	11
Type 5	3-Phase primary, no secondary	18
Type 7	3-Phase primary and neutral, no secondary	62

Table 2-1
Types of Distribution Lines

Line Type	Description	Number of Residences
Type 8	1-Phase primary, secondary with common neutral	215
Type 9	1-Phase primary, secondary with separate neutrals	8
Type 10	2-Phase primary, secondary, phase-phase connection	42
Type 11	3-Phase primary, secondary with phase-phase connection	16
Type 12	3-Phase primary, secondary with common neutral	99
Type 13	3-Phase primary, secondary with separate neutrals	15
Type 14	Two 3-phase primaries, no neutrals, no secondary	1
Type 16	Two 3-phase primaries with neutral, no secondary	4
Type 17	Two-phase primaries, no neutral, secondary with phase-phase connection	2
Type 18	Two 3-phase primaries, secondary with common neutral	5
Type 20	Two-3-phase primaries, secondary with separate neutral	2
Type 21	2-Phase primary, secondary with common neutral and phase-ground connection	21
Type 22	3-Phase primary plus 1-phase primary with secondary	2
Type 23	Transmission lines (69 kV or above)	21
Type 24	2-Phase primary, 4- or 5-wire secondary using two transformers to provide 120 / 240 V and 240 V 3-phase	6
Type 25	2-Phase primary and neutral, phase-ground connections, no secondary	6
Type 26	2-Phase primary and neutral, phase-phase connections no secondary	2
Type 27	4-Wire secondary only	2
Type 28	3-Phase primary, 4-wire secondary using three transformers to provide 120/240 V and 240 V 3-phase	2

Table 2-1
Types of Distribution Lines

Line Type	Description	Number of Residences
	Information not available	2
	Total	996

No attempt was made to divide underground distribution lines into different line types from the point of view of magnetic field generation.

2.4 Highest Distribution Line Magnetic Fields in Areas Accessible to the Public

The highest magnetic fields produced by distribution lines to which the public may be exposed generally occur directly underneath an overhead distribution line or directly above an underground distribution line. The measurements performed during the 1000 home study included a "lateral profile" of the magnetic field for each distribution line located within 100 feet of the residence. A lateral profile consisted of magnetic field measurements every foot from one side of the line to the other, past the residence. Measurements were made with two recorders placed 1.5 and 3.5 feet above ground. Measurements were made of the 60 Hz, 180 Hz, and total harmonic distortion. From each profile data, the largest measured magnetic field value, or "peak magnetic field" was extracted.

Figure 2-1 shows the probability of peak magnetic field near a power line exceeding a given value. Fifty percent of the surveyed residences were near power lines with a peak magnetic field above 0.7 mG. Ten percent of the residences were near lines with peak fields exceeding 3.6 mG and 5% of the residences were near lines where the peak magnetic field exceeded 5.8 mG. Figure 2-1 includes data from all types of power lines near residences.

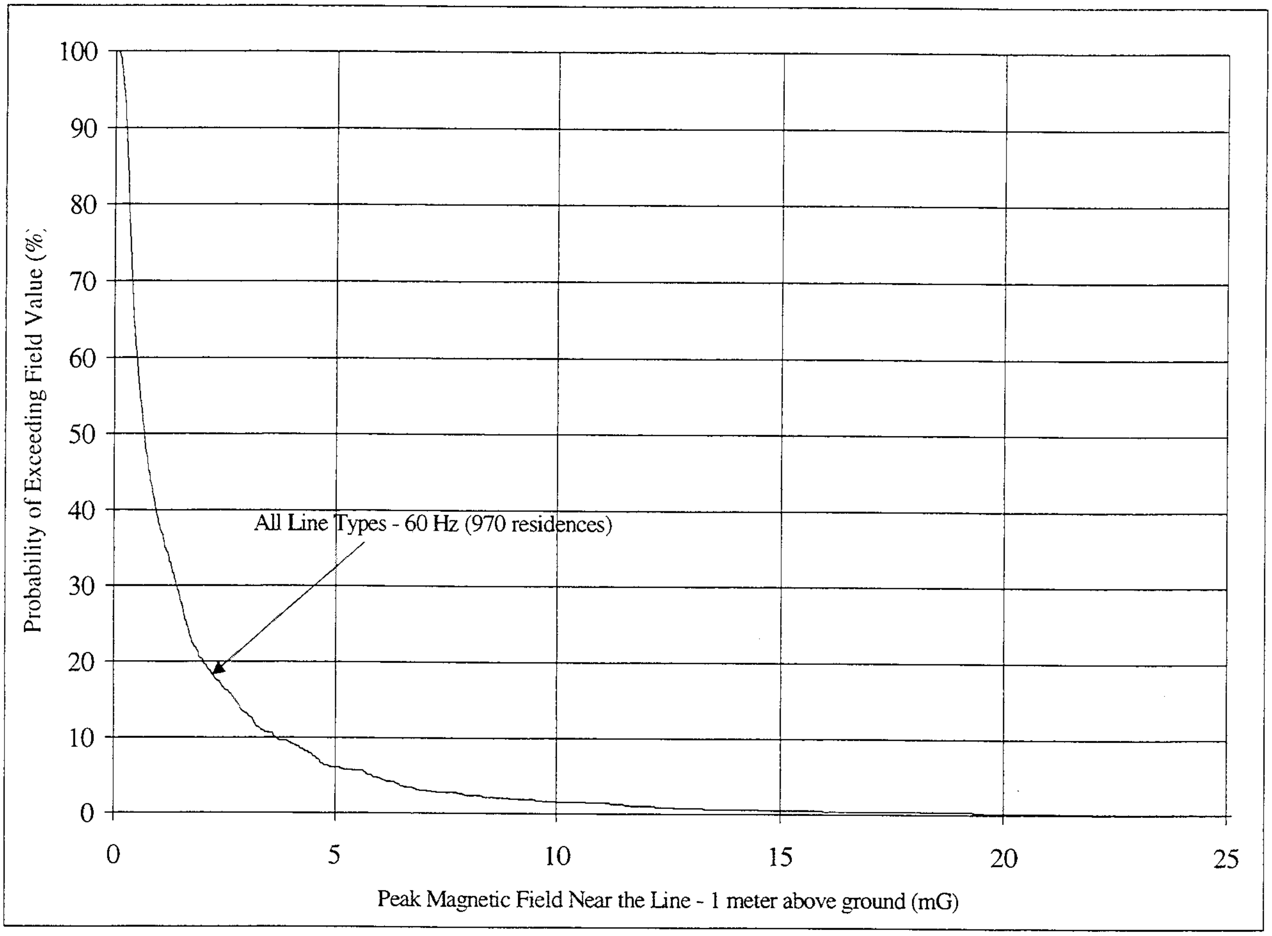

Figure 2-1 Percentage of residences in which the peak magnetic field near the associated power line exceeded a given value. Data is provided for all types of power lines near residences

Figure 2-2 provides more detailed data for different types of distribution lines. It shows the probability of peak magnetic fields near various types of distribution lines exceeding a given value. Three phase distribution primaries have the highest peak magnetic field of any of the distribution line types. The second highest peak magnetic fields are associated with distribution secondaries only (with no primary conductors present). In general, distribution secondaries alone produced higher peak magnetic fields near the line than either single phase or two phase primaries with secondaries.

Since the greatest interest is in the larger fields, the bottom portion of Figure 2-2 was enlarged and is shown in Figure 2-3.

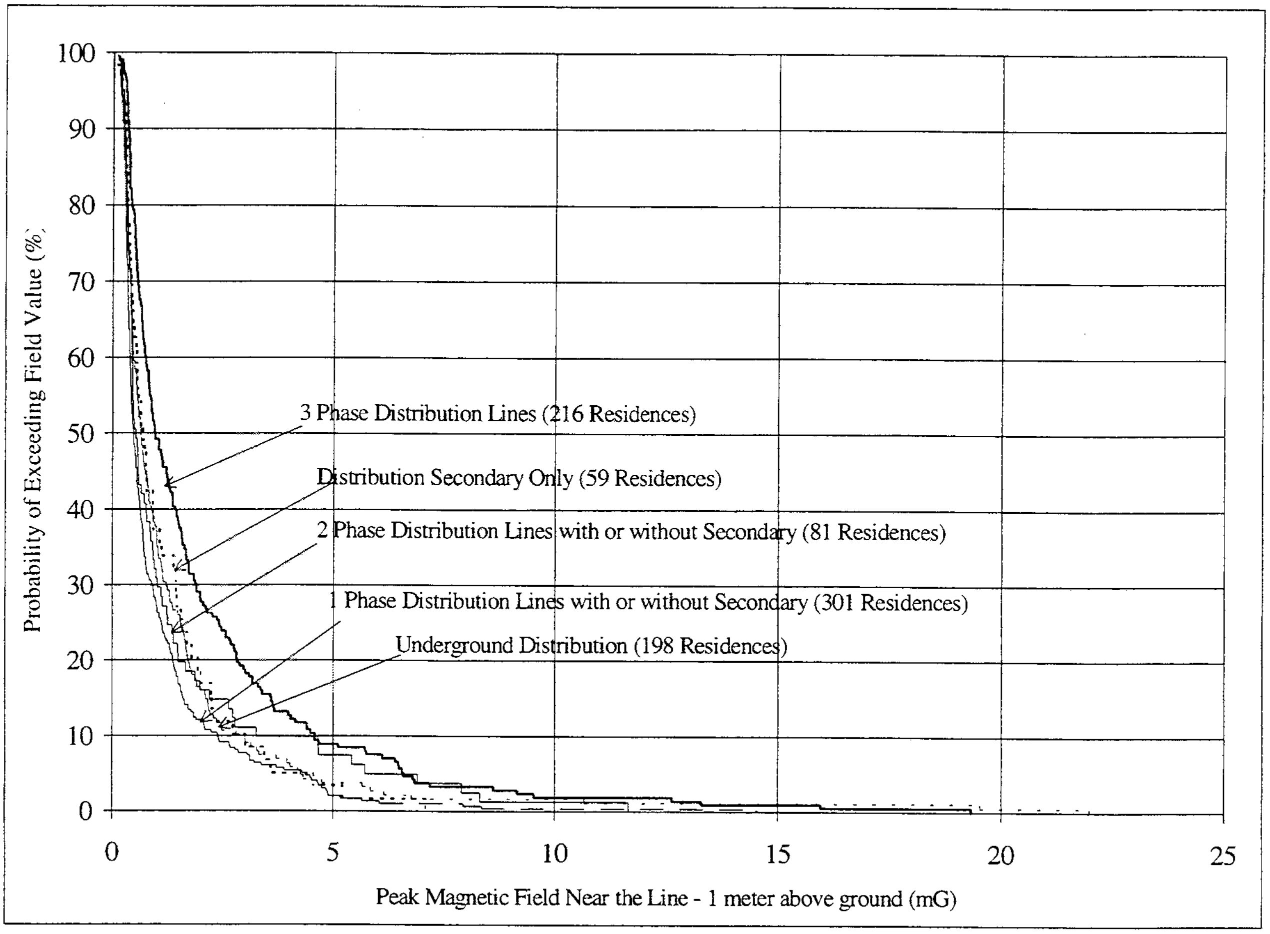

Figure 2-2 Percentage of residences in which the peak magnetic field near the associated distribution line exceeded a given value

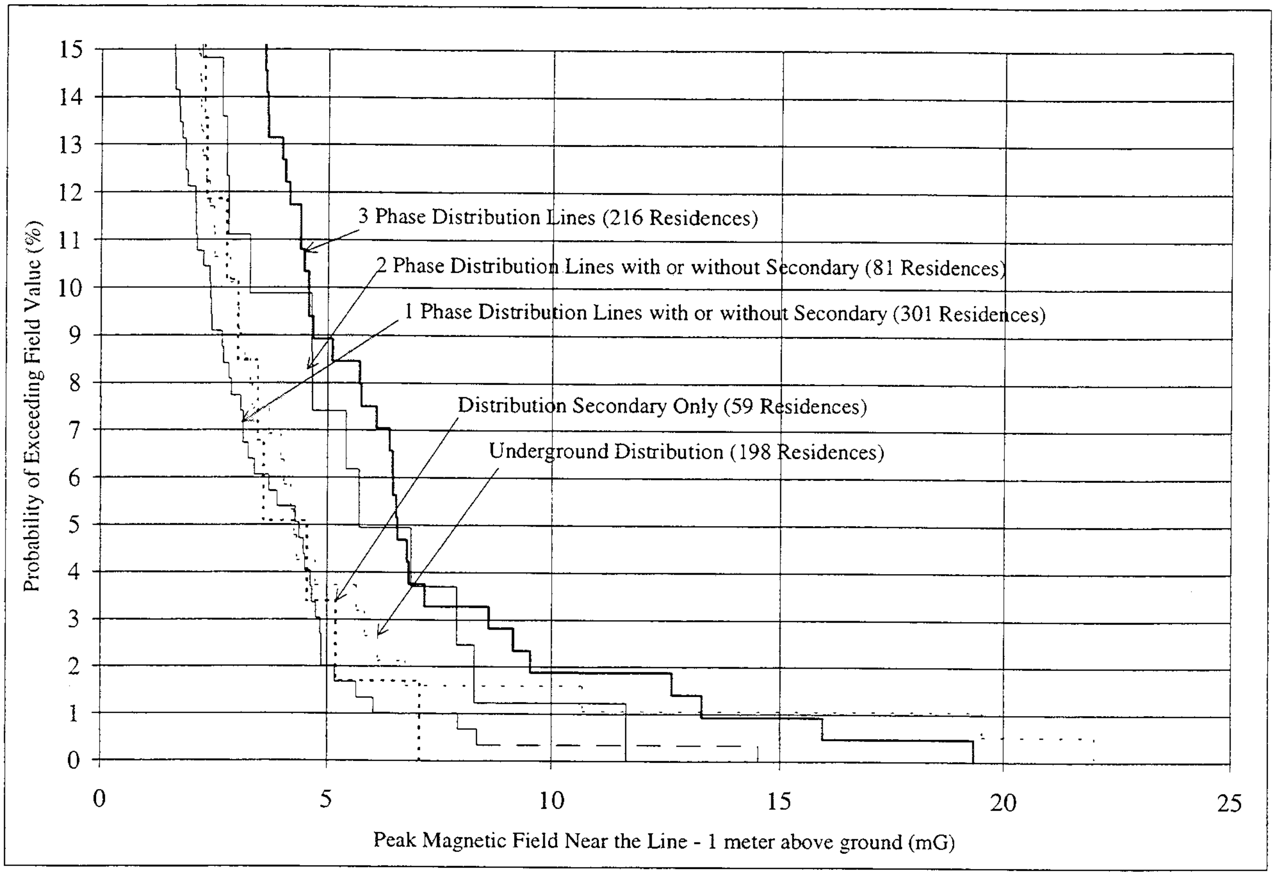

Figure 2-3 Percentage of residences in which the peak magnetic field near the associated distribution line exceeded a given value (same as Figure 2-2, but with an enlarged scale)

Figure 2-4 shows the probability of peak magnetic field near underground distribution lines exceeding a given value. Magnetic field measurement data is presented for 1.5 feet and 3.5 feet above ground. Fifty percent of the surveyed residences near underground distribution lines had peak magnetic fields above 0.6 mG (3.5 feet above ground) and 0.7 mG (1.5 feet above ground).

Ten percent of the residences near underground distribution lines had peak values near the line exceeding 3.0 mG (3.5 feet above ground) and 4.1 mG (1.5 feet above ground), while 5% had peak values exceeding 4.3 mG (3.5 feet above ground) and 7.4 mG (1.5 feet above ground). Referring back to Figure 2-1, underground distribution lines as a group had lower peak magnetic fields than any other distribution classification at approximately 1 meter above ground. However, at 1.5 feet above ground the peak fields associated with underground distribution lines are close to the peak fields associated with overhead three phase distribution primaries.

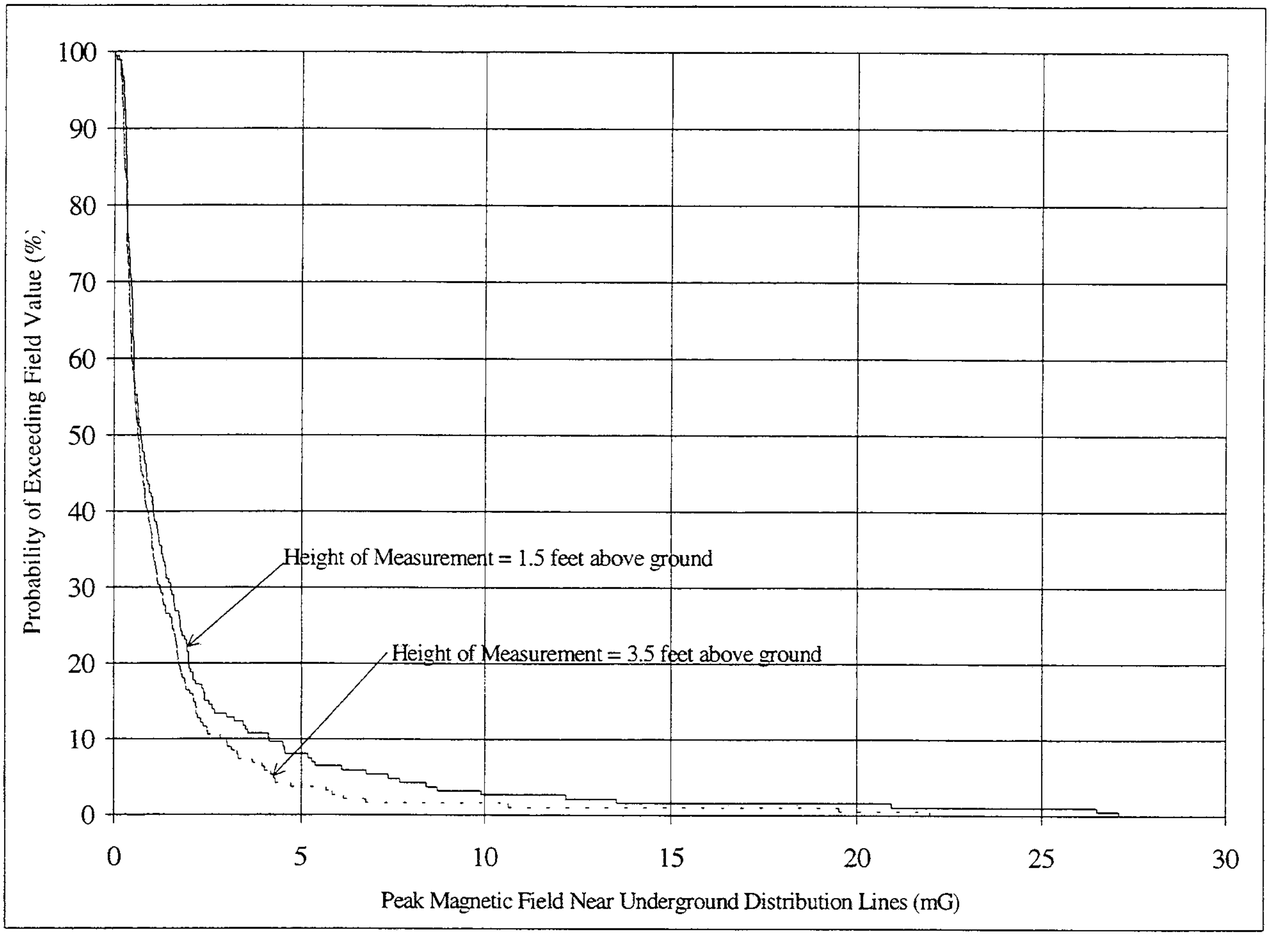

Figure 2-4 Percentage of residences in which the peak magnetic field near underground distribution lines exceeded a given value. Data is provided for 1.5 foot and 3.5 foot measurement heights

The third harmonic of the magnetic field is generally much lower than the 60 Hz component or "Fundamental". Figure 2-5 shows the probability of the third harmonic (180 Hz) component of the peak magnetic field near transmission and distribution lines exceeding a given value. In 50% of the residences surveyed near power lines, the third harmonic component of the magnetic field near the line exceeded 0.25 mG. The third harmonic component exceeded 0.45 mG in ten percent of the residences and exceeded 0.8 mG in five percent of the residences.

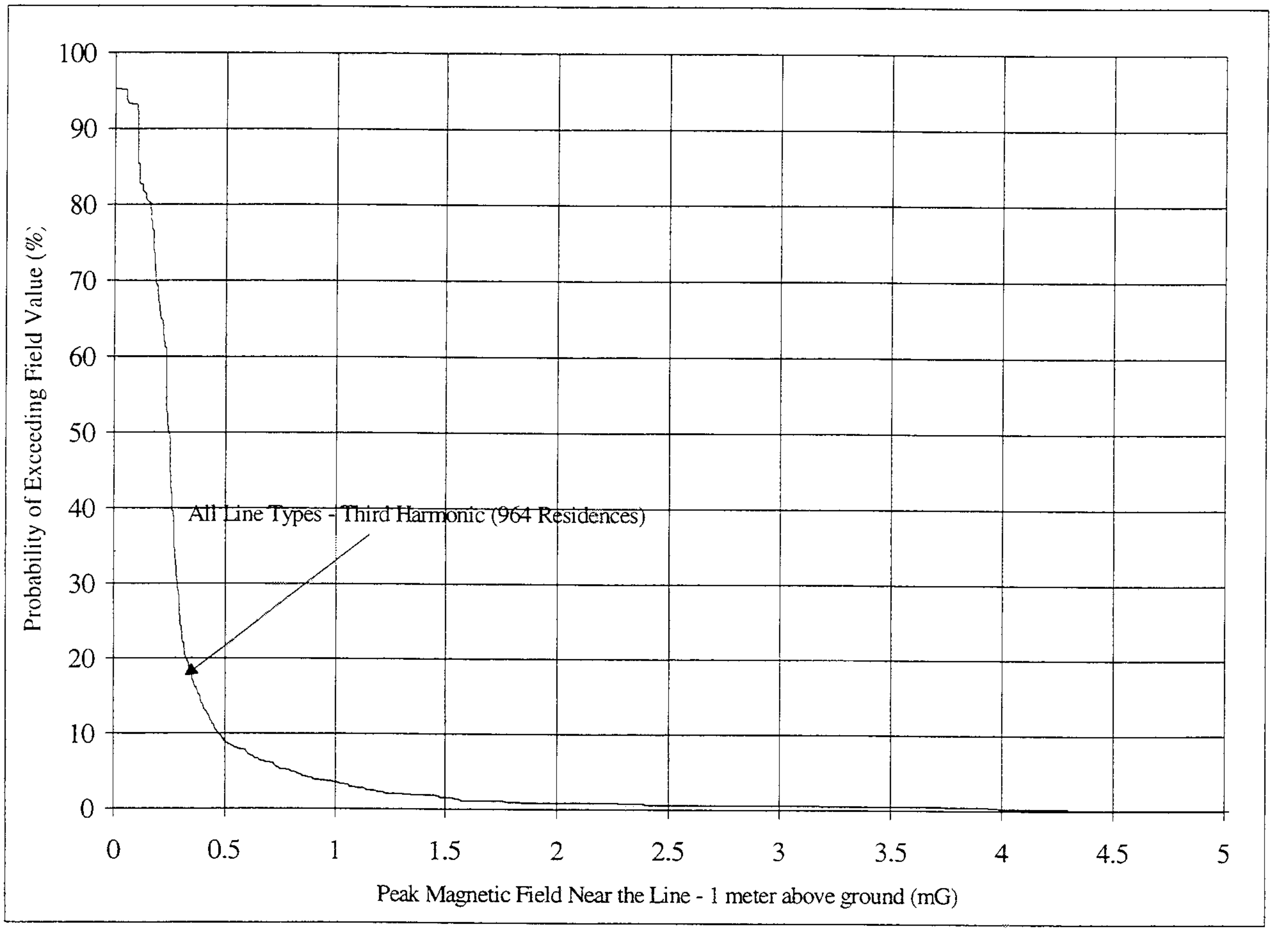

Figure 2-5 Percentage of residences in which the third harmonic peak magnetic field near the associated power line exceeded a given value. Data is provided for all types of power lines including overhead and underground transmission and distribution lines

Figure 2-6, which is similar to Figure 2-5, presents data of the peak total harmonic field near power lines. The total harmonic field is defined as the rms value of the magnetic field after the 60Hz component is subtracted. The total harmonic field of a pure 60Hz field is zero. The total harmonic distortion field in combination with the fundamental (60Hz) component gives the rms value of the magnetic field (60Hz plus harmonics). The rms value of the magnetic field is equal to the square root of the sum of the squares of the 60 Hz component and of the total harmonic field. In 50% of the residences surveyed near power lines, the total harmonic field exceeded 0.3 mG, in 10% the value exceeded was 0.6 mG, and in 5% the value exceeded was 0.9mG. These values are very close to the corresponding points on Figure 2-5 for third harmonic. The third harmonic is the dominant component of the total harmonic field associated with the surveyed power lines.

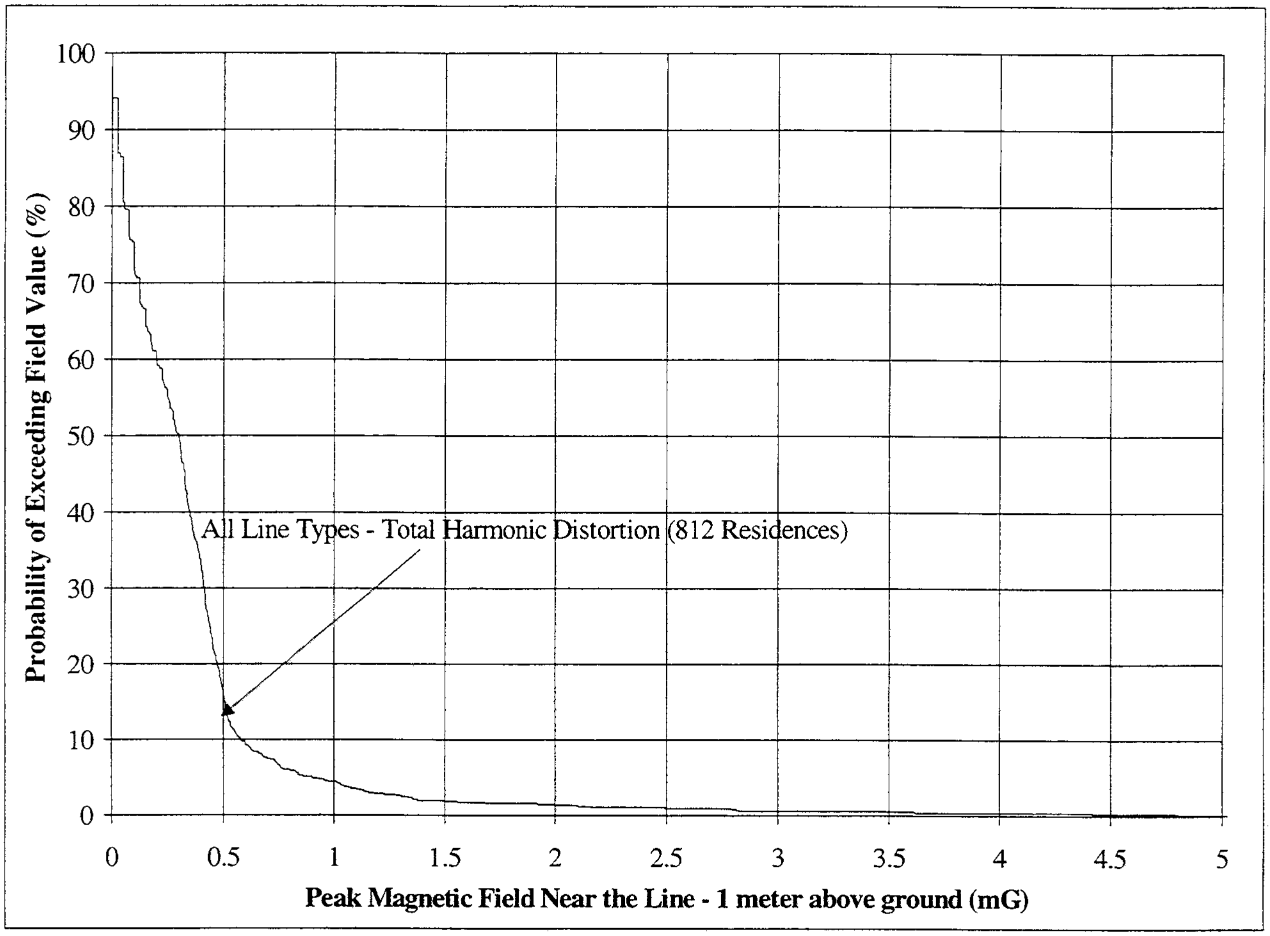

Figure 2-6 Percentage of residences in which the total harmonic distortion peak magnetic field near the associated power line exceeded a given value. Data is provided for all types of power lines including overhead and underground transmission and distribution lines

2.5 Distribution Line Magnetic Fields Inside Residences

The 1000 home study data show that the **average field from distribution lines in the residence** living space over a 24-hour period **exceed 0.4mG in 50%, 1.3mG in 10%, 1.9 mG in 5%, and 3.5 mG in 1% of the homes.** Above average magnetic fields will exist in at least one of the rooms of the home and at some time during the day. A quantity that expresses these higher fields is the "top 5% field" of the residence, which is the field exceeded in 5% of measurements made uniformly in the living space and over a 24 hour period. **The top 5% field caused by distribution lines exceeded 0.7mG in 50%, 2.4mG in 10%, 3.7mG in 5%, and 6.7mG in 1% of the homes.**

Figures 2-7 presents the probability of the average residential magnetic field caused by distribution lines exceeding a given value. Figure 2-8 presents the same data but with an enlarged scale to show the probability distribution corresponding to the largest fields in greater detail.

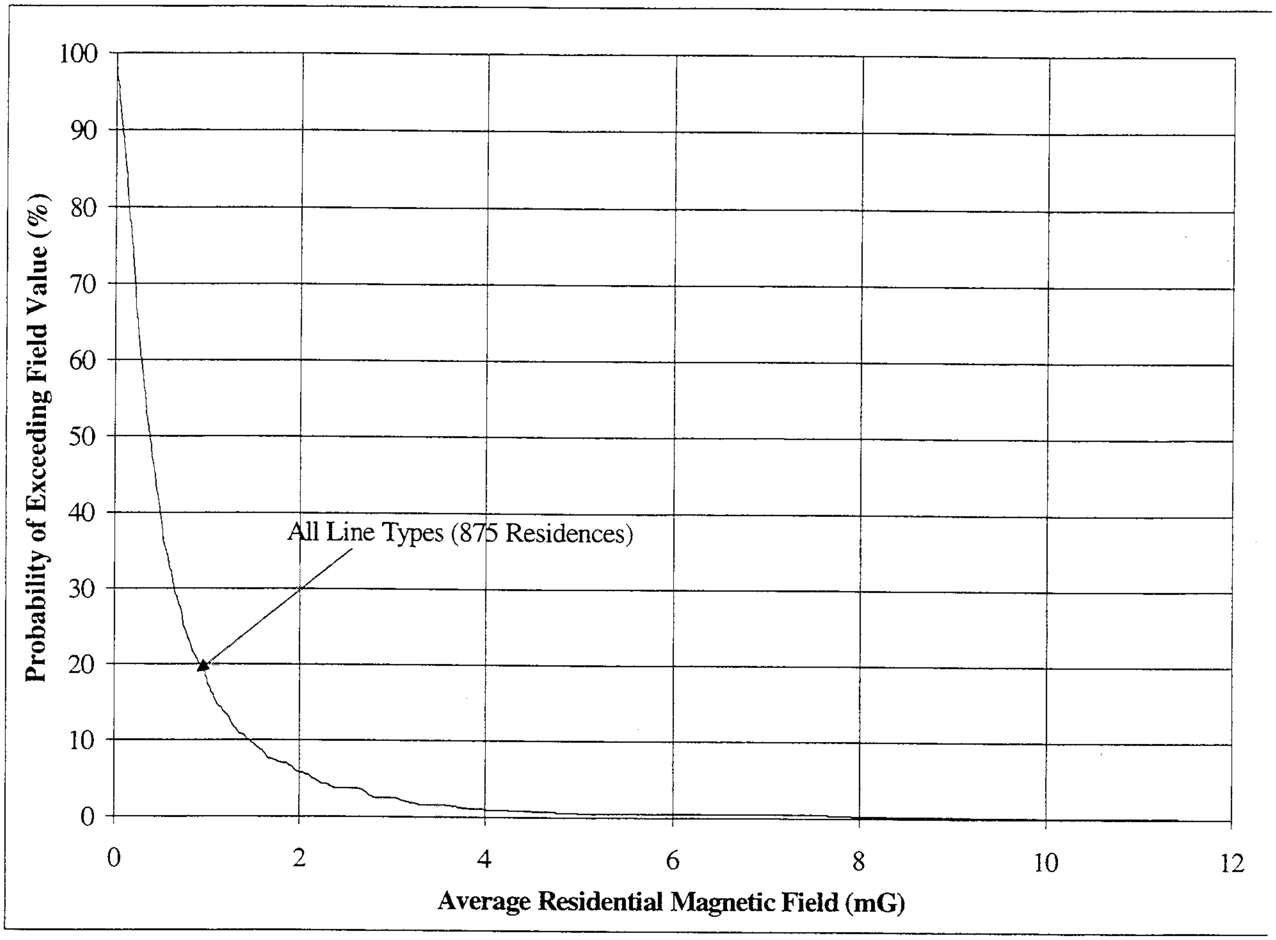

Figure 2-7 Percentage of residences in which the average residential magnetic field caused by external power lines exceeded a given value. Data is provided for all types of power lines including overhead and underground transmission and distribution lines

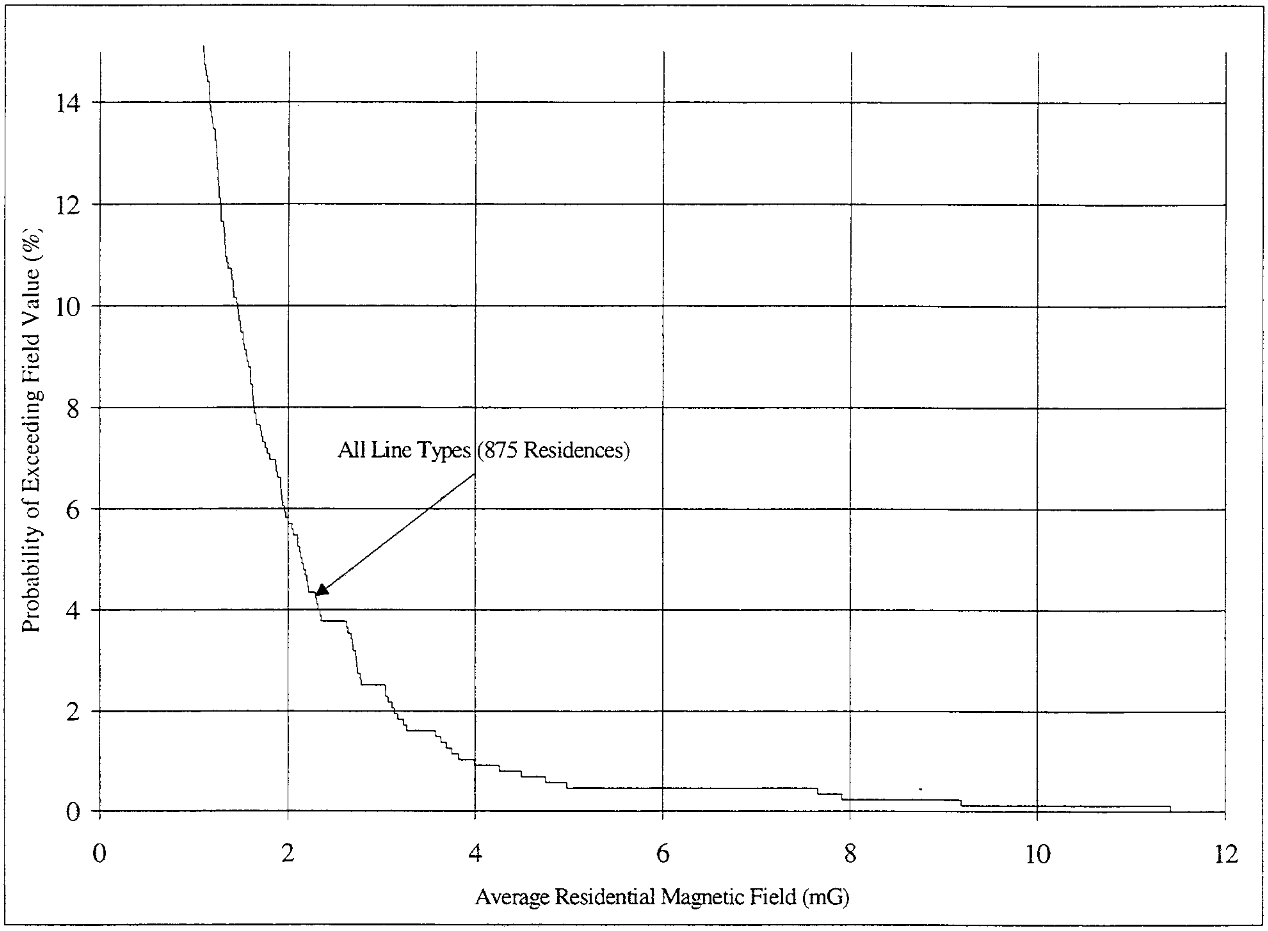

Figure 2-8 Percentage of residences in the average residential magnetic field caused by external power lines exceeded a given value. Data is provided for all types of power lines including overhead and underground transmission and distribution lines (same as Figure 2-7, but with an enlarged scale)

Figure 2-9 presents data corresponding to different types of distribution line configurations. The order of distribution line type which causes the highest average magnetic field is the same as the order of line type which causes the highest peak magnetic field near the line (see Figure 2-2). Three phase distribution primaries cause the highest average residential magnetic field of all distribution line classifications. The lowest average magnetic fields in residences are caused by underground distribution lines. Figure 2-10 presents the same data but with an enlarged scale to show the probability distribution corresponding to the largest fields in greater detail.

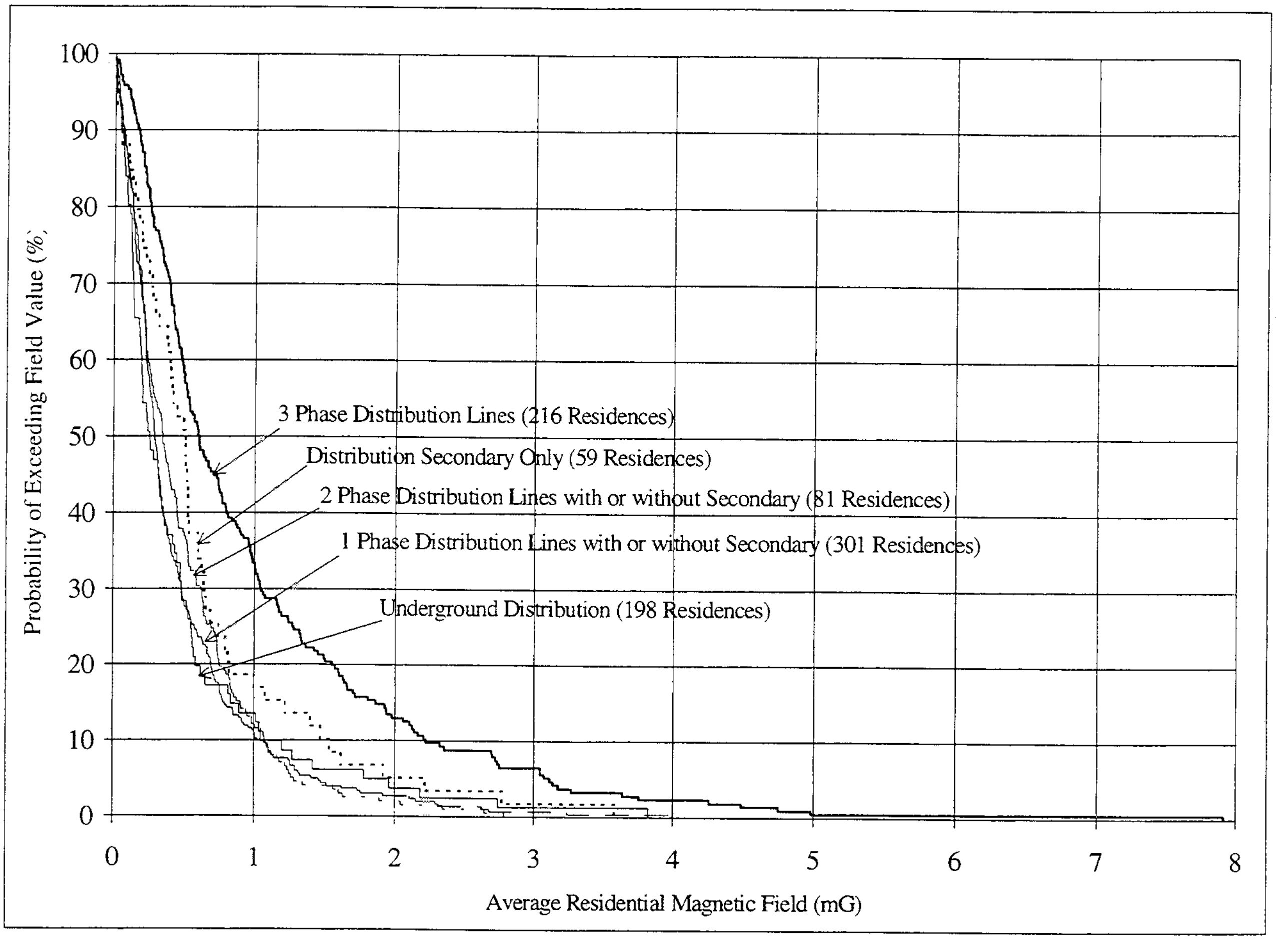

Figure 2-9 Percentage of residences in which the average residential magnetic field caused by various combinations of distribution primary and secondary configurations exceeded a given value

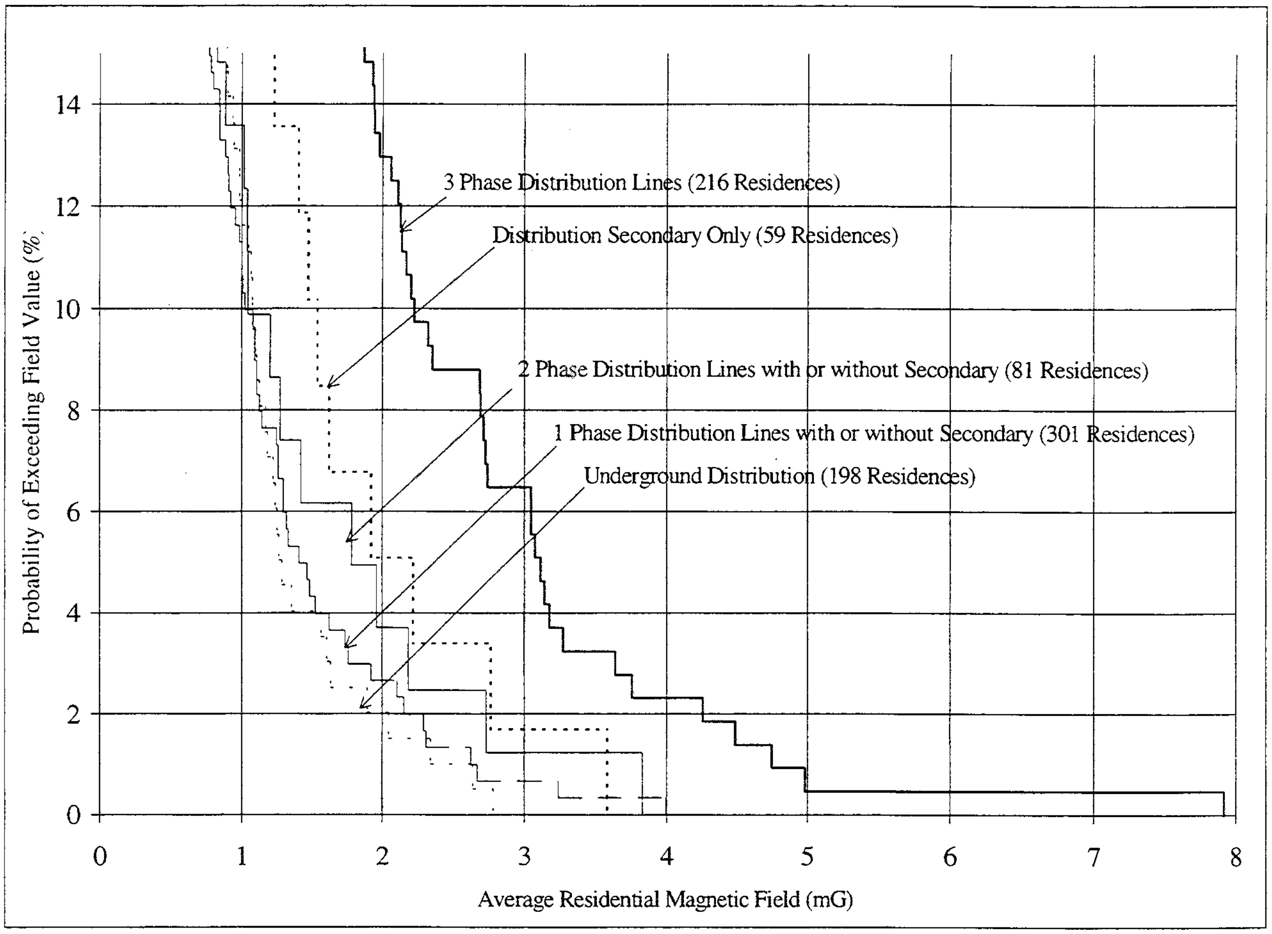

Figure 2-10 Percentage of residences in which the average residential magnetic field caused by various combinations of distribution primary and secondary configurations exceeded a given value (same as Figure 2-9, but with an enlarged scale)

Figure 2-11 presents the results of analyzing the average residential magnetic field data in a different manner. If three phase distribution primaries are excluded, and the remaining distribution classifications are regrouped to identify which type of secondary conductor configuration is used, the dominant line type becomes the open bus secondary (secondary conductors separated by a few feet). For all residences surveyed with overhead distribution secondaries, the largest average magnetic fields are caused by open bus secondary configurations, and the smallest average fields are associated with triplex secondaries (120V wires twisted around the neutral). This effect is independent of the presence of single or two phase primary wires.

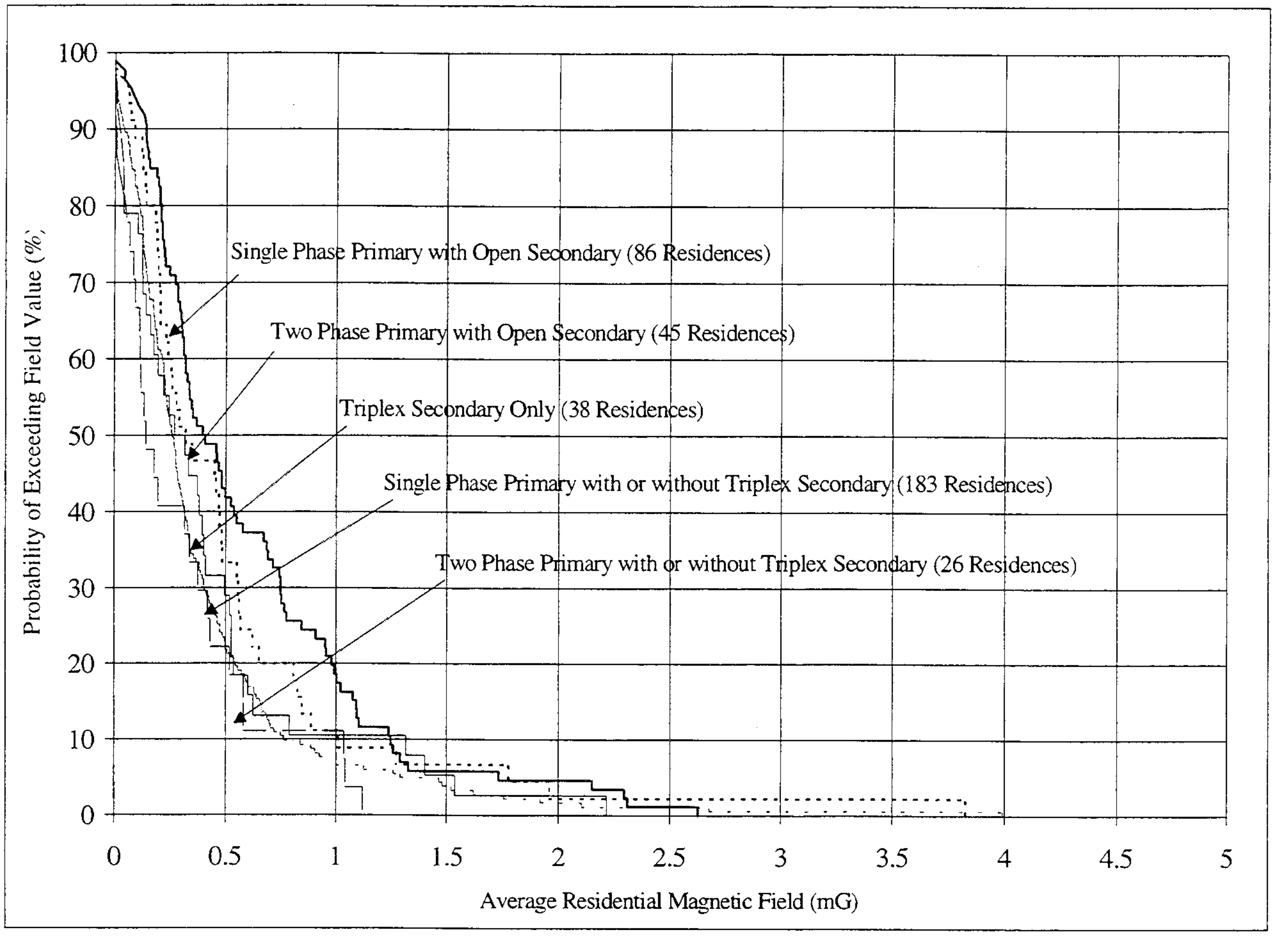

Figure 2-11 Percentage of residences in which the average residential magnetic field caused by various combinations of distribution primary configurations with open or triplex secondaries exceeded a given value

2.6 References

1. "Survey of Residential Magnetic Field Sources", Volumes 1 and 2, EPRI TR-102759, September 1993

3

REPRESENTATIVE 3-PHASE DISTRIBUTION LINE FEEDERS DATA

3.1 EPRI's Distribution Power Quality Node Project

Statistically significant and representative data on the levels of average current, current unbalance, and net current in three-phase distribution lines in the United States are provided by EPRI's Power Quality Node Research Project.

The primary deliverable of the EPRI research program "An Assessment of Distribution System Power Quality" is a database of power quality statistics, typical of distribution systems in the United States. The database provides statistics on the following quantities:

- Voltage Disturbances - rms voltage variations and subcycle transients
- Steady State Characteristics - regulation, harmonic distortion, and phase unbalance

The data was collected from a random selection of 100 distribution feeders from EPRI member utilities throughout the United States. Each feeder was monitored at three different locations for a total of 300 node sites. The first monitor for each feeder was placed at or near the substation. The two other monitoring locations for a particular feeder were selected at random by sectionalizing the feeders. The section lengths were determined by isolating large loads and important distribution equipment such as capacitors, reclosers, sectionalizers, and line branches. Each feeder was divided into three to twenty (or more) sections. The two additional monitoring sites were selected at random for each feeder. Data were collected every 30 minutes. Thus, one compete year of data contains about 17,500 values for each variable.

3.2 Distribution Feeder Current Data

The entire monitoring process began in June 1993 and was completed in September 1995. Not all 300 sites were monitored for the entire duration. The following charts for the remainder of this section were prepared with a sample of node data from 12/93 through 11/94. In an effort to determine representative data for the distribution line current parameters (balanced current, unbalanced current, and net current) described in an earlier section, a sample of 130 sites was analyzed. The sample sites consisted of grounded wye connected feeders. When possible, all three sites from a particular feeder were included. Of the 130 sites analyzed, complete sets of data, including neutral currents, were obtained for 68 sites. The following figures refer to these 68 sites.

The following data of interest for the assessment of magnetic fields were extracted from the data base: phase current magnitude and phase angle at 60 Hz and at 180 Hz, and neutral current magnitude and phase angle at 60 Hz and at 180 Hz. From these data the following quantities were calculated: average phase current (equal to arithmetic average of the three phase currents), unbalanced current (equal to the vectorial sum of the three phase currents), and the net current (equal to the vectorial sum of the three phase currents and the neutral current).

Figure 3-1 shows the probability of the average line 60Hz phase current exceeding a given value. Half of the 68 sites analyzed exceeded 32.4 A 50% of the time and 67A 5% of the time. One percent of the sites studied exceeded 162 A average phase current 50% of the time.

The average 180 Hz (third harmonic) phase current values are much smaller, as shown in Figure 3-2. Half of the sites exceeded 1.0 A 50% of the time and 1.7 A 5% of the time. The top 1% of the sites exceeded 5.2 A average 180Hz phase current half of the time.

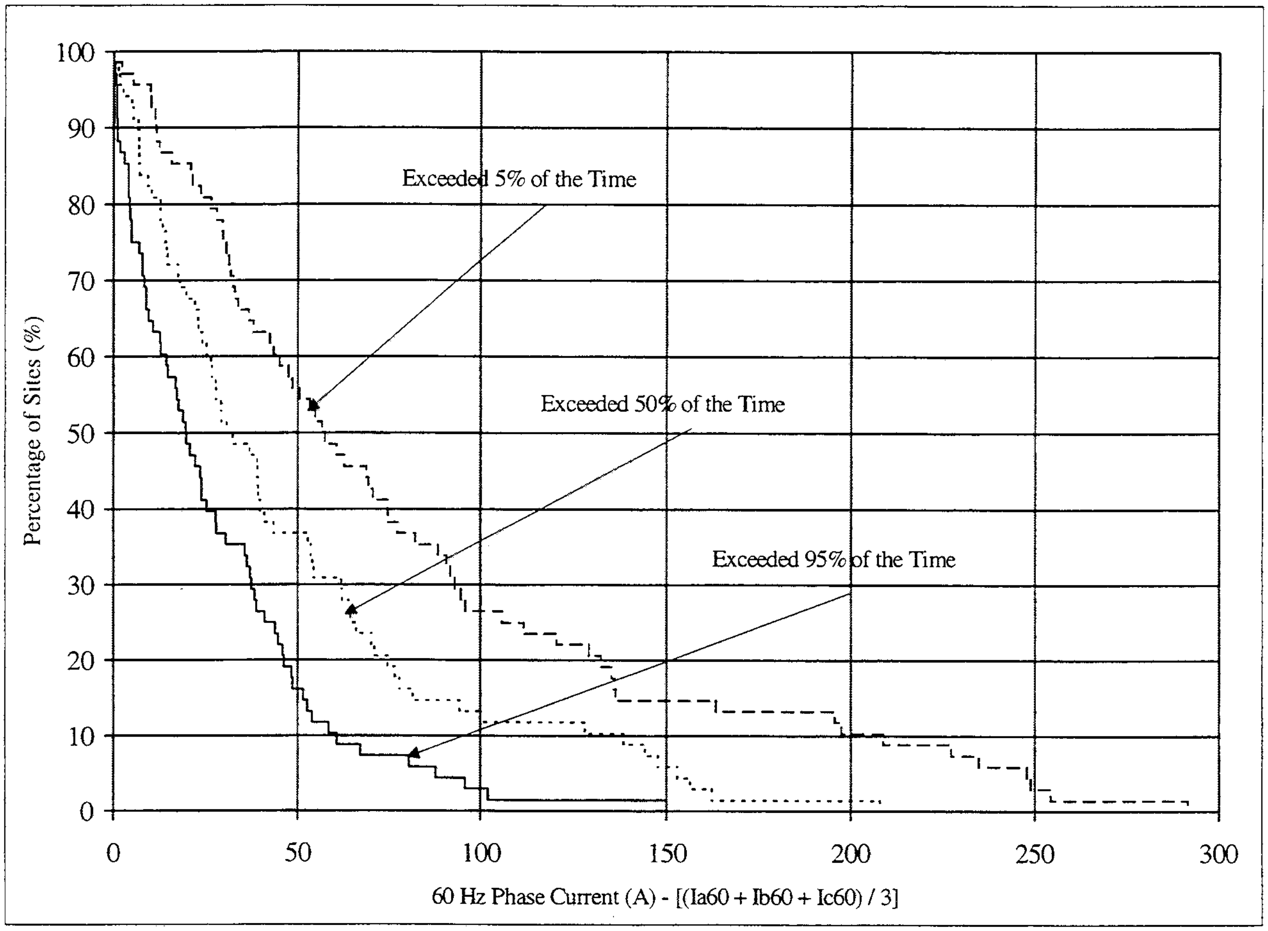

Figure 3-1 Percentage of sites at which the average 60 Hz phase current exceeded a given value (available data is provided for 68 sites from 12/1/93 through 11/30/94)

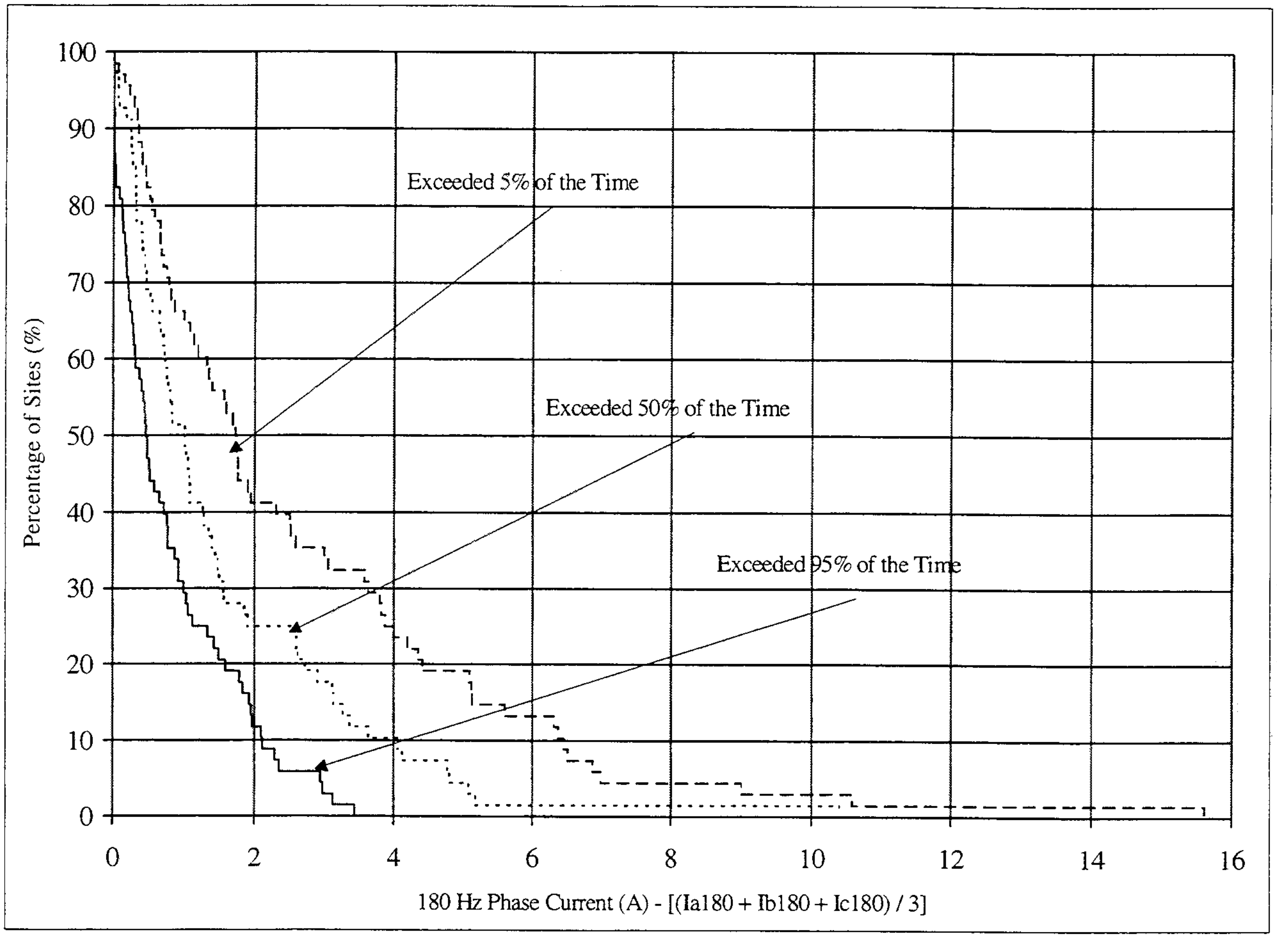

Figure 3-2 Percentage of sites at which the average 180 Hz phase current exceeded a given value (available data is provided for 68 sites from 12/1/93 through 11/30/94)

Figure 3-3 and 3-4 present data for the unbalance current component of the distribution line feeder currents. Figure 3-3 shows that the median value of the 60 Hz unbalanced current exceeded 9.9A for 50% of the sites and 37.4 A for 5% of the sites. The corresponding data in Figure 3-4 show the median value of the third harmonic unbalanced current exceeded 2.4 A for 50% of the sites and 14.4 A for 5% of the sites.

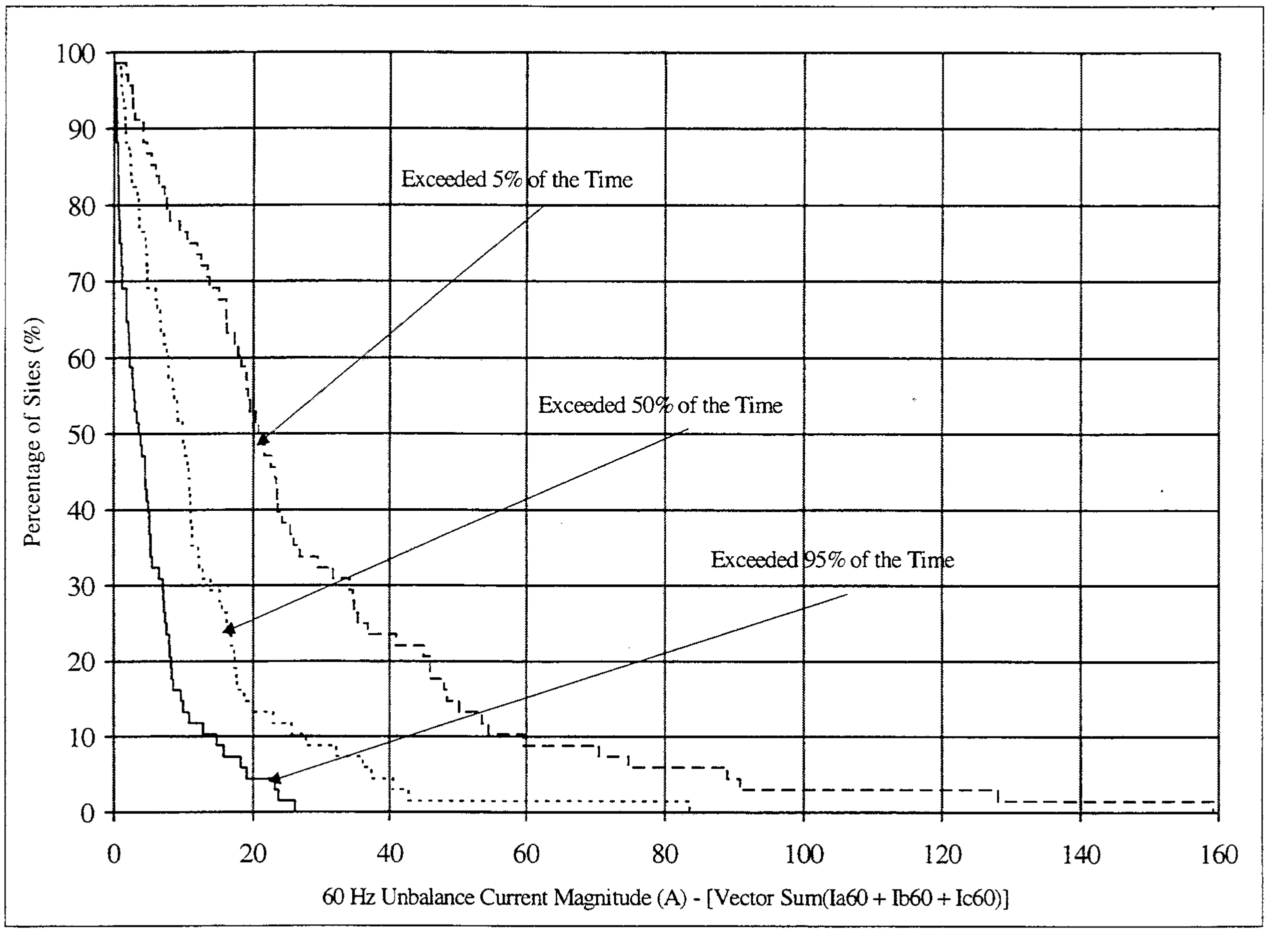

Figure 3-3 Percentage of sites at which the 60 Hz unbalance current magnitude exceeded a given value (available data is provided for 68 sites from 12/1/93 through 11/30/94)

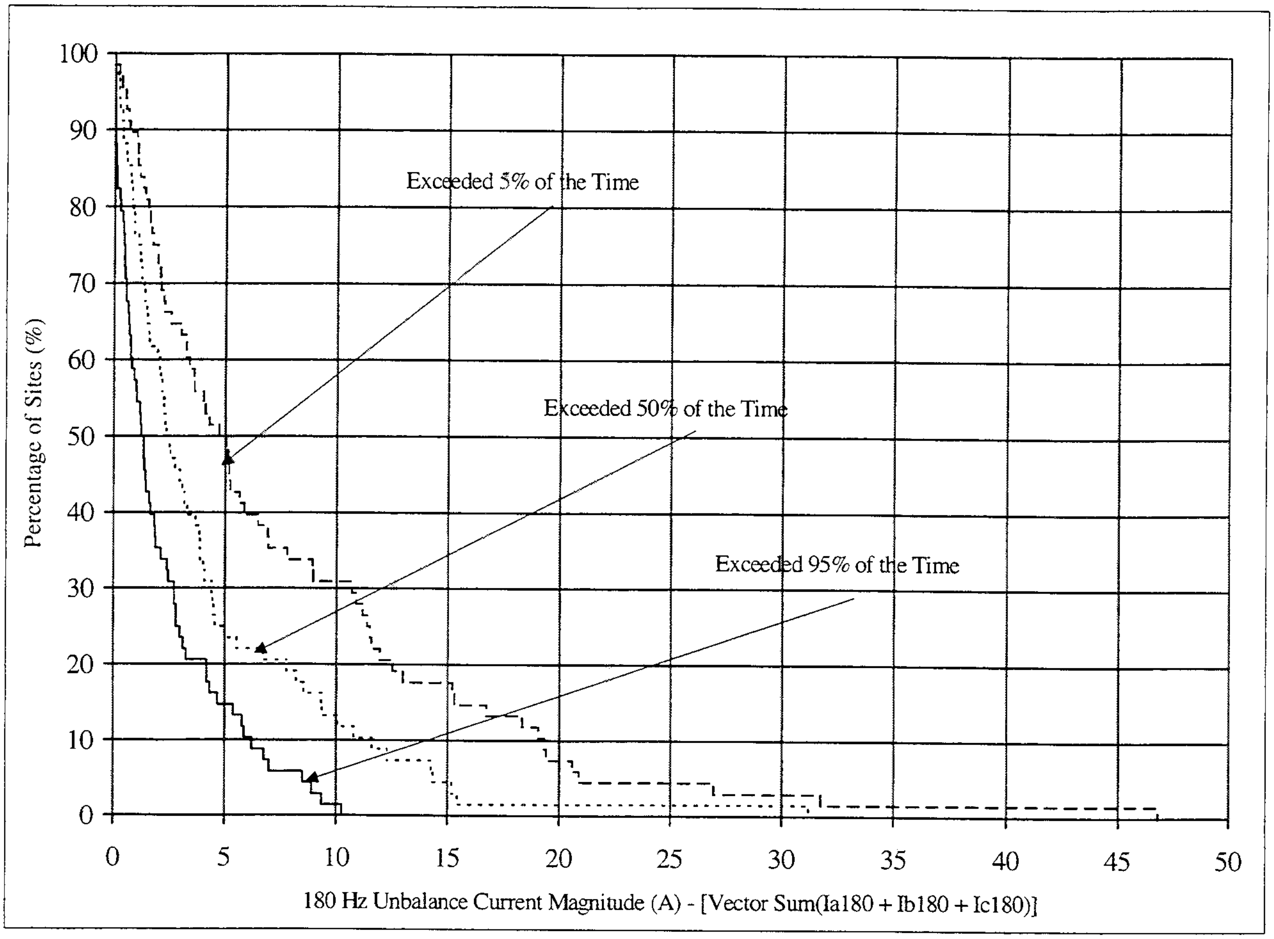

Figure 3-4 Percentage of sites at which the 180 Hz unbalance current magnitude exceeded a given value (available data is provided for 68 sites from 12/1/93 through 11/30/94)

The net current values are shown in Figures 3-5 and 3-6 for 60 Hz and 180 Hz, respectively. The median value of net current exceeded 8.1 A for 50% of the sites, 40.1 A for 5% of the sites, and exceeded 47.3 A for 1% of the sites. The median value of the 180 Hz component of the net current exceeded 2.2 A for 50% of the sites, 15.6 A for 5% of the sites, and 18.7 A for 1% of the sites.

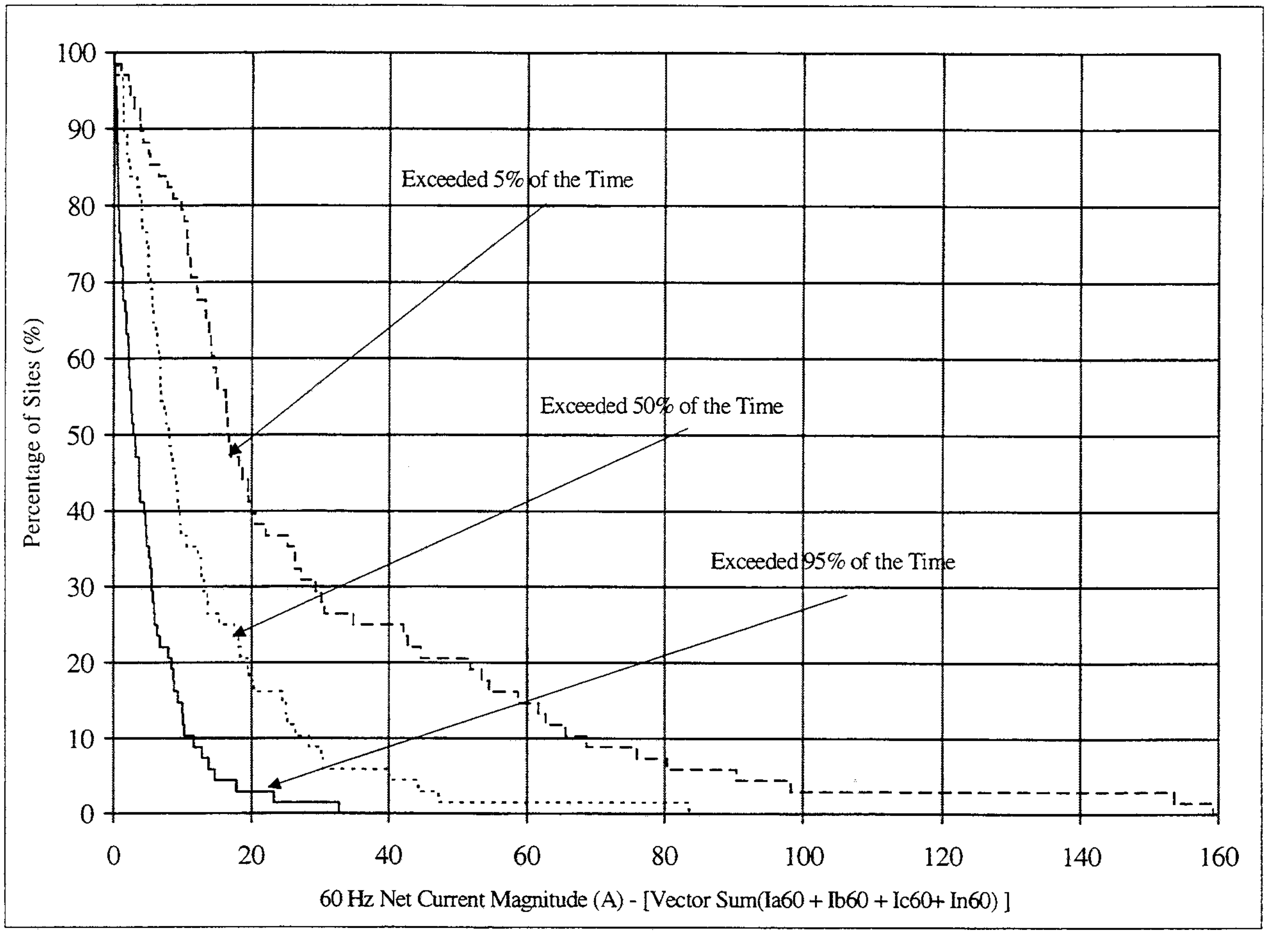

Figure 3-5 Percentage of sites at which the 60 Hz net current magnitude exceeded a given value (available data is provided for 68 sites from 12/1/93 through 11/30/94)

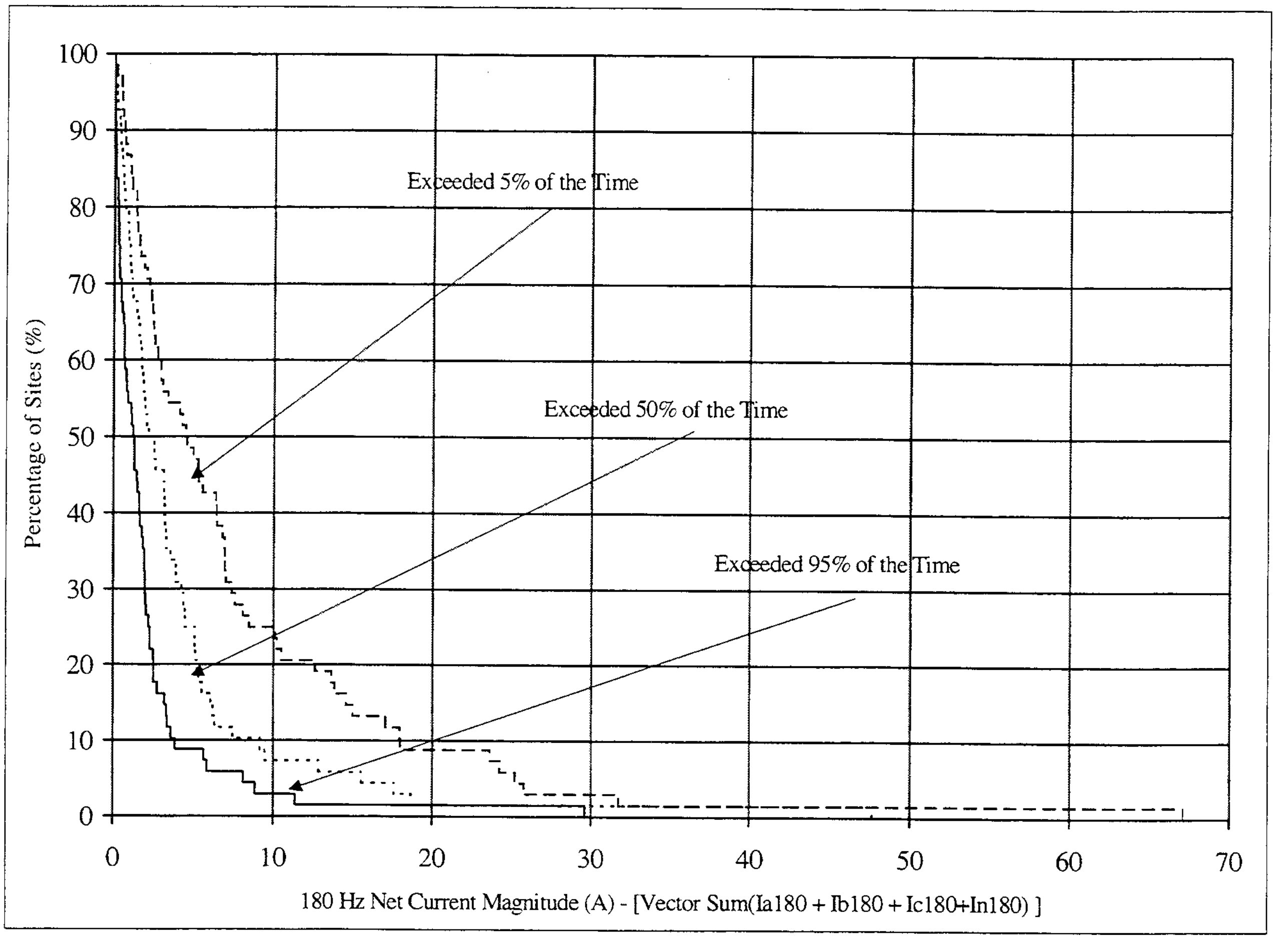

Figure 3-6 Percentage of sites at which the 180 Hz net current magnitude exceeded a given value (available data is provided for 68 sites from 12/1/93 through 11/30/94)

3.3 Application of Distribution Feeder Current Data

The data presented in Figures 3-1 through 3-6 may be used in conjunction with simplified equations for 4-wire distribution lines presented in Section 4 to calculate statistics pertaining to the magnetic field near 3-phase distribution line feeders.

For example, the data could be used to asses the magnetic field at various distances from 4-wire 3-phase distribution line feeders. For this task, the geometry of the line must be specified. Assume, for instance, a cross arm arrangement with 6 feet between the outer phases and about 6 feet between the neutral and the phase wires as shown in Figure 3-7. According to the equations developed in Section 4, the balanced, unbalanced, and ground components of the field are given by:

$$B_p = \frac{\sqrt{2}\, P_{ebc}\, I_{av}}{R^2} \qquad \text{(eq.3-1)}$$

$$B_u = \frac{2\, I_u\, P_{pu}}{R^2} \qquad \text{(eq.3-2)}$$

$$B_g = \frac{2\, I_{uet}}{R} \qquad \text{(eq.3-3)}$$

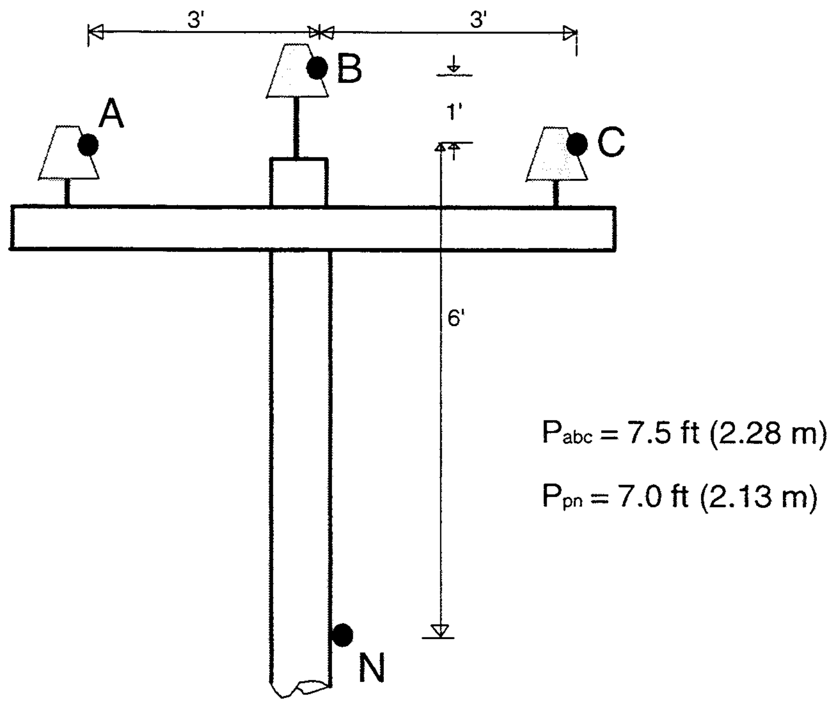

Figure 3-7 Example distribution line geometry for magnetic field calculations

Tables 3-1 and 3-2 present magnetic field data calculated using the currents from Figures 3-1 through 3-6, and equations 3-1 through 3-3. The balanced component of the magnetic field in Table 3-2 is negligible because the 180 Hz currents in the phase conductors are not balanced. In general, these third harmonic currents are nearly in phase and their sum produces the unbalance current at 180 Hz. In all cases of current and distance combinations in Tables 3-1 and 3-2, the ground current component of the magnetic field is the largest of the three components.

Table 3-1
60 Hz magnetic field data based on PQN database currents (Figures 3-1 through 3-6) for conductor geometry shown in Figure 3-7

	Field at 25 feet		Field at 75 feet	
Field Components	**50% of sites 50% of time**	**top 5% of sites top 5% of time**	**50% of sites 50% of time**	**top 5% of sites top 5% of time**
Balanced	1.80 mG	13.75 mG	0.20 mG	1.53 mG
Unbalanced	0.73 mG	6.54 mG	0.08 mG	0.73 mG
Ground	2.10 mG	23.7 mG	0.71 mG	7.91 mG

Table 3-2
180 Hz magnetic field data based on PQN database currents (Figures 3-1 through 3-6) for conductor geometry shown in Figure 3-7

	Field at 25 feet		Field at 75 feet	
Field Components	**50% of sites 50% of time**	**top 5% of sites top 5% of time**	**50% of sites 50% of time**	**top 5% of sites top 5% of time**
Balanced	Negligible	Negligible	Negligible	Negligible
Unbalanced	0.18 mG	1.53 mG	0.02 mG	0.17 mG
Ground	0.58 mG	6.62 mG	0.19 mG	2.20 mG

Analysis of the PQ Node data for unbalance current and net current shows that in many cases, the net current is larger than the unbalance. In these cases, the distribution feeder neutrals are carrying current from other primary or secondary circuits. The resulting net current component of the magnetic field is the dominant component. In these cases, the majority of the magnetic field both near the conductors (at ground level) and farther away is dominated by the net current. Investigation of the large net currents may be the subject of future EPRI research.

4

CALCULATION OF MAGNETIC FIELD FROM DISTRIBUTION LINES

4.1 Two - and Three - Dimensional Geometry. EPRI Software

The general method of calculation of magnetic field for a two-dimensional geometry consisting of a set of parallel wires of known location and current is described in reference [1]. This method applies to many distribution line situations, when the effects of sags, line angles, and unequal pole geometry can be neglected. The two-dimensional method provides useful "first approximation" results and allows assessments of the line parameters that may affect magnetic fields.

For more accurate field calculations a three-dimensional approach must be used. This is accomplished by dividing the line conductors into several straight segments and calculating the field from each segment using the law of Biot-Savart [2]. In this way the combined effect of conductor sags, unequal geometry of two adjacent poles, line turns, laterals, service drops, and water pipe currents can be taken into account. These and other variables can be addressed in a user friendly manner with RESICALC, a versatile EPRI software tool described in Appendix A. Examples of RESICALC calculation outputs for a two-dimensional and a three-dimensional situation are shown in Figures 4-1 to 4-4.

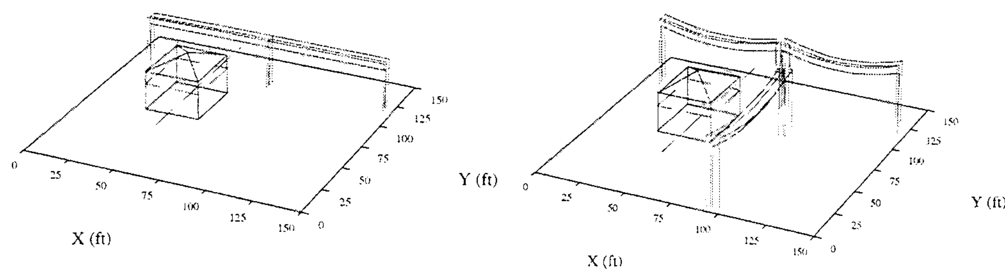

Figure 4-1 Sketch of geometry for two and three dimensional examples

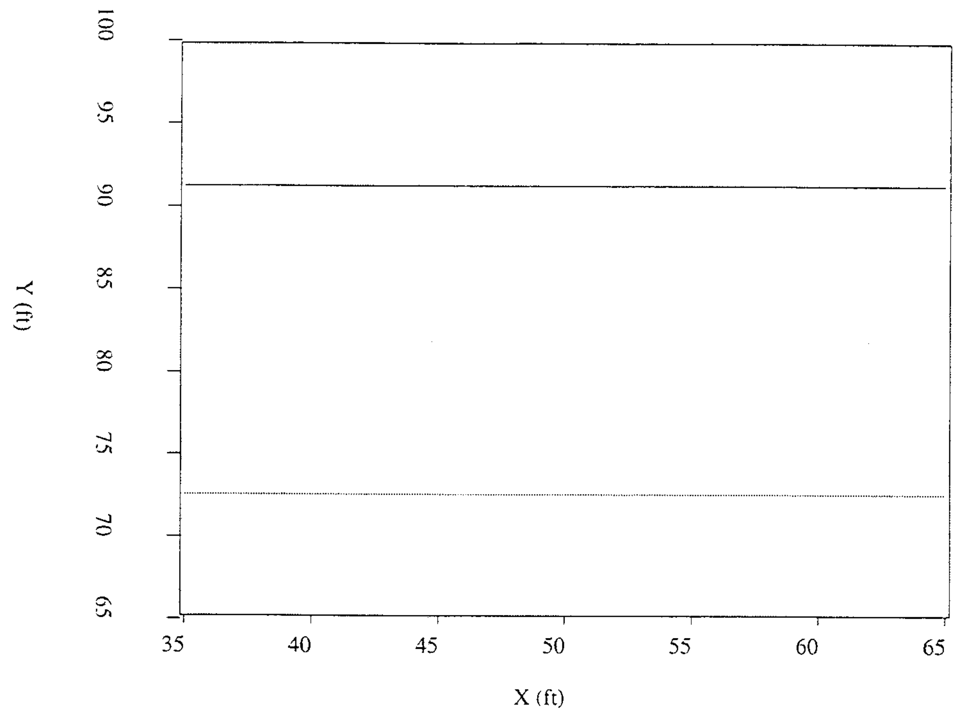

Figure 4-2 Contour line example from RESICALC (2-D)

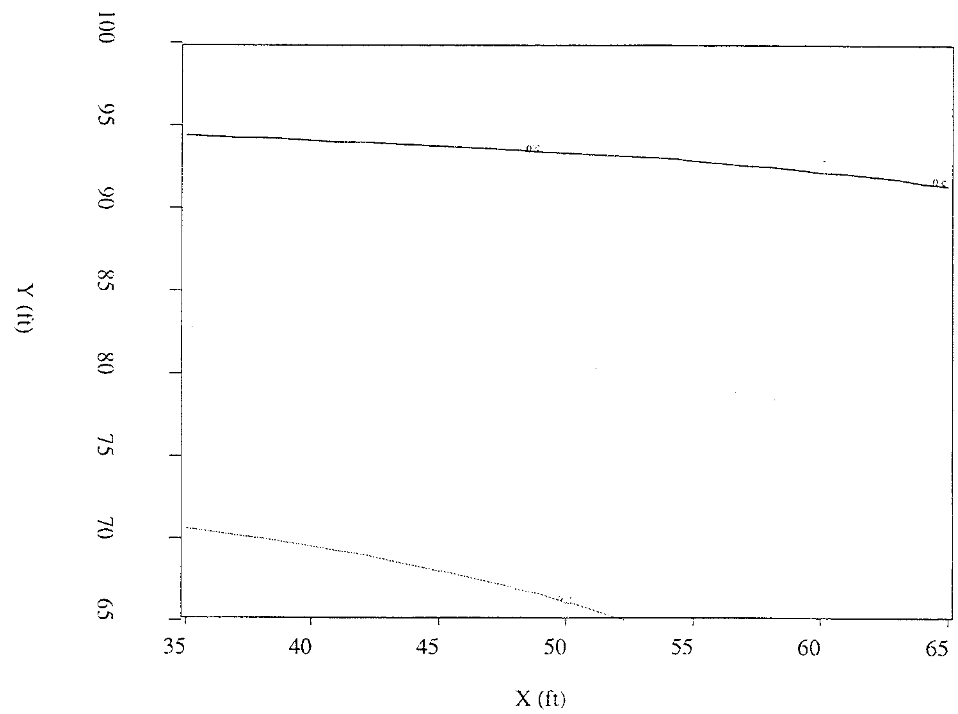

Figure 4-3 Contour line example from RESICALC (3-D)

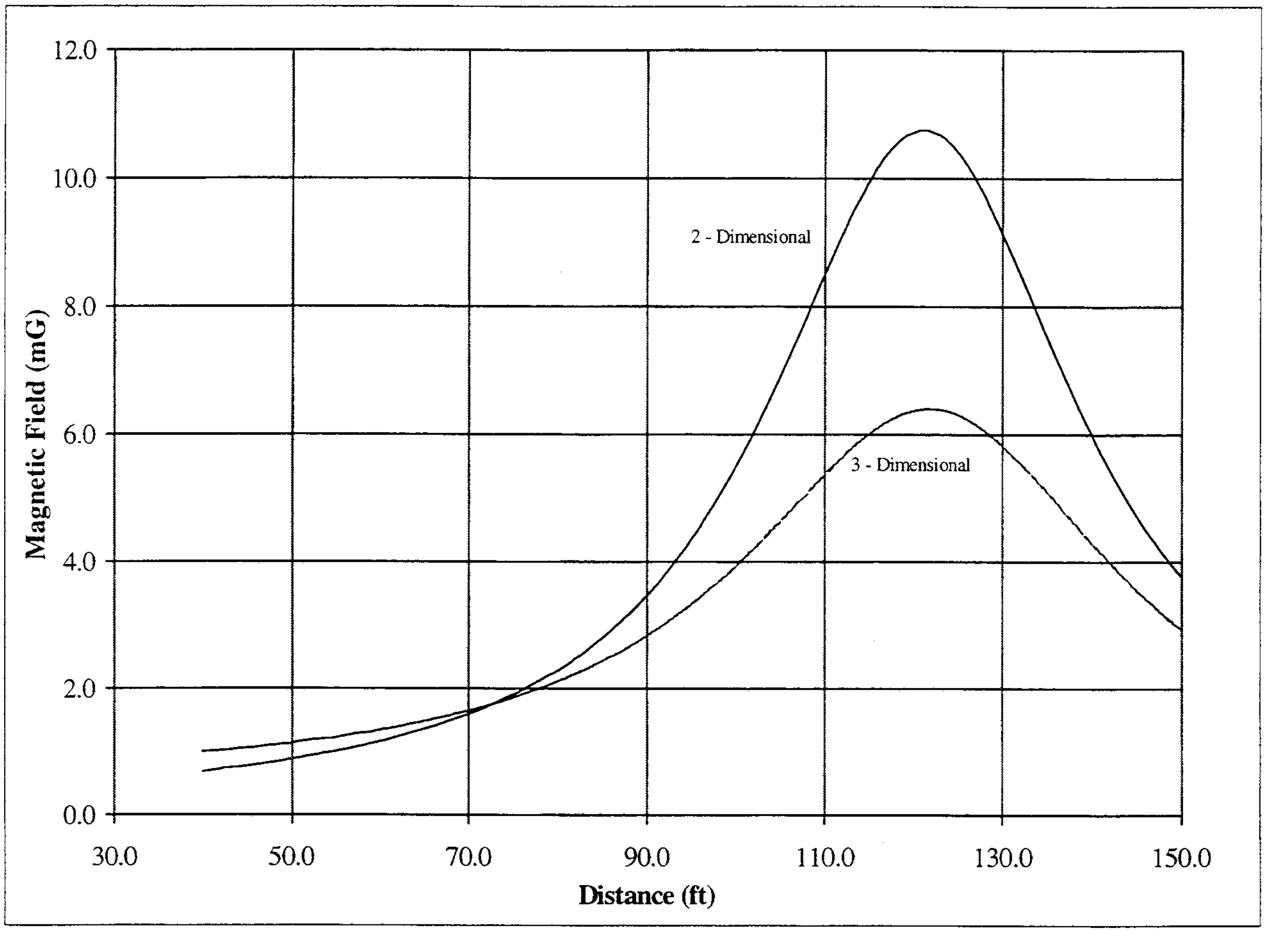

Figure 4-4 Lateral profiles: 2-D and 3-D examples

4.2 Effect of Three-Phase Line Unbalance and Net Current. Simplified Equations

Two different distribution systems are considered: a three-phase, 4-wire multi-grounded, common-neutral primary system, which is used in most regions of the United States and a three-phase, 3-wire primary system, which is widely used in California.

For both 3 and 4-wire systems, the phase current magnitudes for phase A, B, and C are defined as: I_a, I_b, and I_c, respectively. Neutral and ground currents are defined as I_n, and I_g, respectively.

4.2.1 Simplified Equations for a 4-Wire System

A three-phase four-wire system with a multi-grounded neutral is illustrated in Figure 4-5.

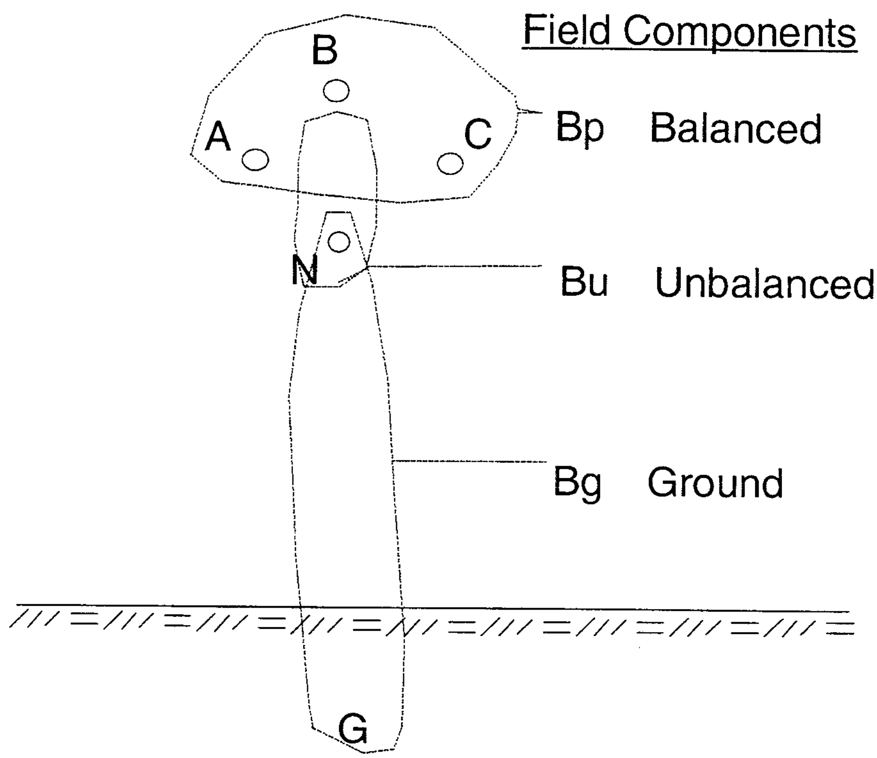

Figure 4-5 The current carrying conductors of a 4-wire system are the three phases A, B, and C, and the neutral conductor N (since the neutral is connected to ground at several points along the line, the ground G may also carry current)

The following quantities are defined:

The average phase current, I_{av}, is:

$$I_{av} = \frac{I_a + I_b + I_c}{3} \qquad \text{(eq.4-1)}$$

Note that the magnitude of the currents, regardless of their phase angle, are entered in equation (4-1).

The unbalance current, I_u, is:

$$\vec{I}_u = \vec{I}_a + \vec{I}_b + \vec{I}_c = -(\vec{I}_g + \vec{I}_n) \qquad \text{(eq. 4-2)}$$

Equation (4-2) considers phasors. Therefore, both amplitudes and phase angles of the phase currents are important in determining the current unbalance.

The unbalance, U, is commonly defined as the ratio between the maximum phase current deviation from the average phase current and the average phase current:

$$U = \frac{MAX\,(|I_a - I_{av}|,|I_b - I_{av}|,|I_c - I_{av}|)}{I_{av}} \qquad \text{(eq. 4-3)}$$

The unbalance given by equation (4-3) is expressed in per unit (or percentage) and cannot be related easily to the unbalance current given by equation (4-2).

The Net Current, I_{net}, is equal to the vectorial sum of all the wire currents. It is also equal and opposite to the ground current:

$$\vec{I}_{net} = \vec{I}_a + \vec{I}_b + \vec{I}_c + \vec{I}_n = -\vec{I}_g \qquad \text{(eq. 4-4)}$$

For a 3-wire system the net current is always zero, because there is no neutral. Every load is connected between phases and no portion of load current flows into the ground.

The Ground Current Ratio, G, is a vector defined as:

$$\vec{G} = \frac{\vec{I}_g}{\vec{I}_u} \qquad \text{(eq. 4-5)}$$

The ground current ratio expresses the fraction of the unbalance current that does not flow into the neutral. This current flows into alternative ground path, not necessarily *in* the ground. For example, a portion of this current may return to the substation through neutrals of other distribution lines. Nevertheless, the terminology "ground current" is used for this quantity. Alternatively, the fraction of the unbalance current that flows into the neutral may be chosen as the parameter to describe the distribution of the unbalance current among the two paths: neutral wire and other ground return paths.

The neutral return ratio, N, is defined as:

$$\vec{N} = \frac{\vec{I}_n}{\vec{I}_u} \qquad \text{(eq. 4-6)}$$

The neutral return ratio, N, is related to the ground return ratio, G, through equation (4-7).

$$\vec{G} + \vec{N} = 1 \qquad \text{(eq. 4-7)}$$

The distance between wires is designated by the letter P with the appropriate subscripts. For example, the distance between phase A and phase B is P_{ab}.

The equivalent phase spacing, P_{abc}, is defined as:

$$P_{abc} = \sqrt{P_{ab}^{\ 2} + P_{ac}^{\ 2} + P_{bc}^{\ 2}} \qquad \text{(eq. 4-8)}$$

The magnetic field B measured at a distance R from the geometric center of the four wires is approximated by the combination of three field components (see Figure 4-5):

Balanced, B_p: The field produced by the phase currents assumed balanced.

Unbalanced, B_u: The field produced by the unbalance current assumed flowing between neutral and phase wires.

Ground, B_g: The field produced by the ground current assumed flowing between the neutral and the ground.

Assumptions: In order to arrive at simplified equations, several assumptions are made. The calculations are made for the "distant field", defined as the field at locations whose distance from the center of the power line conductors is much greater (more than 5 times) the average distance between the phase conductors.

It is assumed that all the currents are 120 degrees apart. Data from EPRI's Power Quality Node Project [3], show this to be an accurate assumption, the deviation from the 120 degree separation being, on average, only about 2 degrees.

The unbalance of the circuit is the most difficult parameter to characterize. Two types of unbalances representing two extreme situations are considered. Equations will be derived for these two unbalance types. All of the unbalance cases will fall somewhere between these two extremes. The two types of unbalance are described as follows:

Type 1 Unbalance: Two phase currents are equal. For example, a Type 1 unbalance could be: I_a = 75 A, I_b = 75 A, and I_c = 150 A. This typically occurs when a disproportionally large single phase load is present on one of the phases.

Type 2 Unbalance: One phase currents is equal to the average phase current, I_{ave}. For example, a Type 2 unbalance could be: I_a = 125 A, I_b = 100 A, and I_c = 75 A. This would be a typical case if the load were normally distributed across the three phases.

The ground current is assumed dispersed enough and/or diverted from the immediate proximity of the distribution line so that its contribution to the local magnetic field is minimal and can be ignored. However, if the ground current returns in total or in part on other utility wires on the same distribution line pole (telephone, cable TV), then the calculated magnetic fields will tend to be greater than actual. How much of the primary current that returns in other utility wires warrants further investigation.

For each magnetic field component and for both types of unbalance, simplified magnetic field equations were derived. The detailed derivation of these equations can be found in Section 4.4. Table 4-1 shows the simplified equations.

Table 4-1
Simplified Equations for 4-Wire Systems

Field component	**Unbalance Type 1**		**Unbalance Type 2**	
Balanced (B_p)	$B_p = \frac{\sqrt{2}P_{abc}I_{av}}{R^2}$	(4-9)	$B_p = \frac{\sqrt{2}P_{abc}I_{av}}{R^2}$	
Unbalanced (B_u)	$B_u \approx \frac{3UI_{av}P_{pn}}{R^2}$ $P_{pn} = \sqrt{P_{bn}^2 + P_{abc}^2 / 18}$	(4-10)	$B_u \approx \frac{3UI_{av}P_{pn}}{R^2}$ $P_{pn} = \frac{\sqrt{10}}{3\sqrt{3}} P_{acn}$	(4-12)
Ground (B_g)	$B_g = \frac{3GUI_{av}}{R}$	(4-11)	$B_g = \frac{2\sqrt{3}GUI_{av}}{R}$	(4-13)

The equations in Table 4-1 for the two types of unbalance are very similar. They are identical for the balanced component. The equations for the unbalanced component are the same except that the value of P_{pn}, the equivalent distance between phase wires and neutral, is different in the two cases, but not by a large amount, (e.g. for a flat phase configuration with phase spacing P and the neutral under the center phase , B, at a distance 2P, equation (4-10) gives P_{pn} = 2.08 P while equation (4-12) gives P_{pn} = 2.28 P, which is only slightly different). Equations (4-11) and (4-13) for the ground component differ by a factor of 1.15.

The type of unbalance that is occurring on a distribution line is not normally known. Since the equations for the two types give similar results and the equations for type 1 unbalance are simpler and more intuitive, they are preferred and will be used in Section 4.3 for a sensitivity analysis.

The magnetic field that results from the combination of the three components of Table 4-1 (balanced, unbalanced, and ground field components) is determined as the "most probable" value, using equation (4-14):

$$B = \sqrt{B_p^{\ 2} + B_u^{\ 2} + B_g^{\ 2}} \qquad \text{(eq. 4-14)}$$

The distances in equations (4-9) to (4-14) must be expressed in meter, the currents in ampere, and the calculated fields are in milligauss.

Equation (4-14) gives magnetic field values in the "distant field" that are generally within a few percentages of the values calculated with RESICALC and differ from the actual field by at most 20% in extreme cases.

4.2.2 Simplified Equations for a 3-Wire System

A three-phase three-wire system has no neutral. Distribution transformers are connected between phases. As a result, the vectorial sum of the 3 phase currents is zero and there is no ground current. The field component due to ground current disappears. The field component due to unbalance is small in relation to the balanced component. The field is approximated by equation (4-9). The distant field is rather insensitive to the value of the unbalance U. When the unbalance is zero, equation (4-9) gives the exact value of the field (far from the line). If the unbalance is 100% equation (4-9) gives results that are within about 20% of the exact value.

4.3 Sensitivity Analysis

4.3.1 Sensitivity Analysis for a 4-Wire System

Equations (4-9), (4-10), (4-11), and (4-14) can be used effectively to study the change in magnetic field caused by varying specific parameters and are suggestive of ways to reduce magnetic field.

Average phase current, I_{av}. All three field components and, therefore, also the total field are proportional to the average phase current. *The magnetic field of a four wire 3-phase distribution line is proportional to the average phase current.* This current can be reduced by splitting the current over multiple circuits or by converting existing lines to a higher operating voltage.

Distance from the wires, R. The balanced and the unbalanced components of the field vary in inverse proportion with the square of the distance, while the ground component of the field varies in a simple inverse proportion with the distance. The ground component becomes comparable to the other two components at some distance from the line that depend on the various line parameters. For distribution lines that have a very compact geometry, such as aerial spacer cables and underground cables, the ground component may dominate at all practical distances. Varying the distance R is most effective for overhead lines with a small ground ratio and small unbalance. R can be increased by moving the line or the subject or increasing the height of the pole.

Equivalent phase spacing, P_{abc}. This parameter has a significant influence on the balanced field (equation 4-9), little effect on the unbalanced field (equation 4-10), and no effect on the ground field (equation 4-11). Varying the phase spacing, therefore, is very effective only for lines for which the balanced component is dominant. The equivalent phase spacing can be reduced by arranging the conductors closer together or configuring them in an optimum arrangement (e.g. delta is preferable to flat).

Unbalance, U. Two of the field components, the unbalanced field and the ground field, are directly proportional to the unbalance (see equations 4-10 and 4-11). Thus this parameter has a large importance when these two components dominate the total field. Since the unbalanced field is usually smaller than the balanced field, this will occur only when the ground current ratio is high. As a consequence, one of the most effective methods to reduce the ground component of the magnetic field is to try to balance the loads on the three phases of the distribution line.

Neutral to phase spacing. This parameter affects the unbalanced field (see equation 4-10). Moving the neutral conductor closer to the phase conductors is effective when the line experiences large unbalance.

Ground current ratio, G. The ground field is proportional to this parameter. A reduction of G achieves an effective field reduction in all cases where the ground current field is predominant. The reduction of G can in general be accomplished by reducing the neutral impedance or increasing the impedance of the ground connections. However, the problem of controlling ground currents is very complex. Some proposed solutions require changes in well established utility practices and may affect safety and reliability of the distribution system.

For instance, net currents are generated because some of the unbalance returns to the distribution substation via the neutrals of other lines. Neutrals are generally interconnected through the system even at locations were the phases are sectionalized. A field reduction technique could consist of sectionalizing the neutral at all locations were the phases are sectionalized. This however would increase the chances of some of the neutral becoming ungrounded (causing a voltage hazard). Additionally, sufficient short circuit current to operate relays and open breakers in substations may not be available in the case of a fault.

Another field reduction technique consists of inserting special transformers in series with the distribution line wires, with all three phases and neutral wires wound on the transformer core. The transformer would constitute a high impedance for a net current, yet a low impedance for balanced loads and for loads that are unbalanced but with the unbalance flowing in the neutral wire. The cost effectiveness of this solution depends on the significance of the ground magnetic field and on the effect that the insertion of a transformer of this type has on other aspects of the system.

Example application:
An example will illustrate the power of the method just described. Assume that field measurements at a school yard near a distribution line show 5 mG at the edge of the playground, 65 ft away from the center of the line. It is desired to reduce the magnetic field to 2.5 mG or less. At the time of the field measurements the average line current is 150 A and the unbalance is 40%. The dimensions are as shown in Figure 4-5.

The equivalent phase spacing (calculated using equation (4-8)) is 2.1 m

The balanced component, calculated according equation (4-9), is 0.75 mG.

The unbalance component, calculated according to equation (4-10), is 1.05 mG.

The ground component, calculated from equation (4-14), on the basis of the measured field and the calculated values of the other two components, is 4.85 mG.

The ground current ratio, G, derived from equation (4-11), is equal to 0.5.

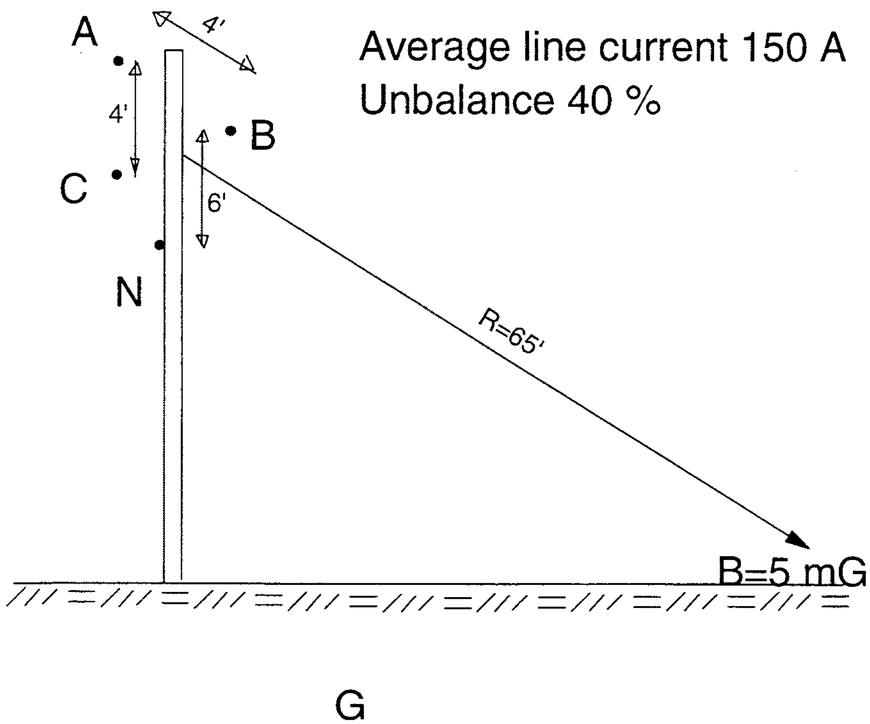

Figure 4-6 Distribution line dimensions for the example

What steps should be taken to reduce the field to 2.5 mG ? A simple analysis of the field equations shows that the following options would accomplish the goal.

- Reduce the average current by one half. This could be achieved by doubling the voltage.
- Reduce the unbalance from 40% to 20%. This could possibly be achieved by balancing the loads served by the line.
- Reduce the ground current ratio from 50% to 25%. An analysis of the reasons why the ground current ratio is relatively large may reveal some conditions that could be modified with relatively minor efforts (e.g.: the neutral is too small or has some bad connection, another neutral offers a shorter return path to the substation).
- Increase the distance R by a factor of 2 to 130 feet by moving the line or the playground fence. Increasing the line height would not be an effective option.
- Adjusting the phase to phase or the phase to neutral distances will have no effect on the field in this situation, because these actions will change the values of the balanced and unbalance fields, which contribute only to a small extent to the total field.

4.3.2 Sensitivity Analysis for a 3-Wire System

For a 3-wire system there are only three parameters that affect the field: average phase current, equivalent phase spacing, and distance from the source (see Equation 4-14). The most practical methods to reduce the field consist in arranging the conductors closer together, configuring them in an optimum arrangement (i.e. delta), and increasing the height of the pole. The effect of these changes are shown in Figure 4-6. It is evident that compacting the geometry, for instance by using spacer cables, is extremely effective in reducing the magnetic field.

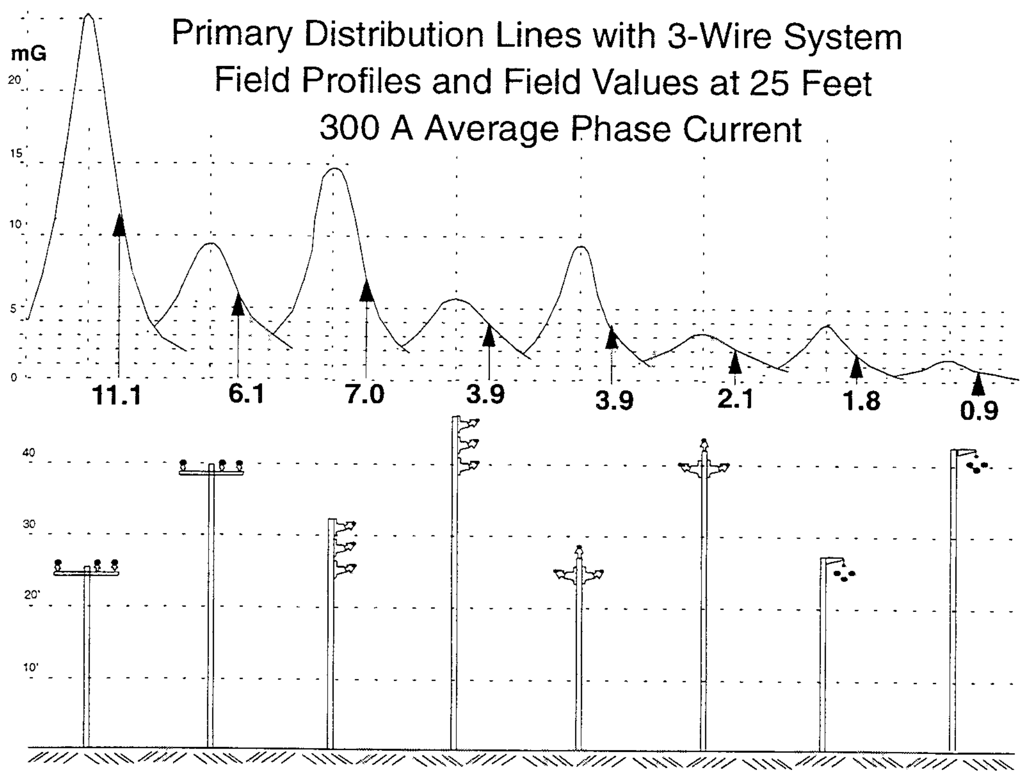

Figure 4-7 Examples of lateral profiles of magnetic field for different types of 3-phase, 3-wire lines

4.4 Derivation of Simplified Equations for 3-Phase Distribution Lines

The system of currents that comprises a 4-wire distribution line can be broken into three components as shown in the Figure 4-6, for unbalance type 1, and in Figure 4-7, for unbalance type 2.

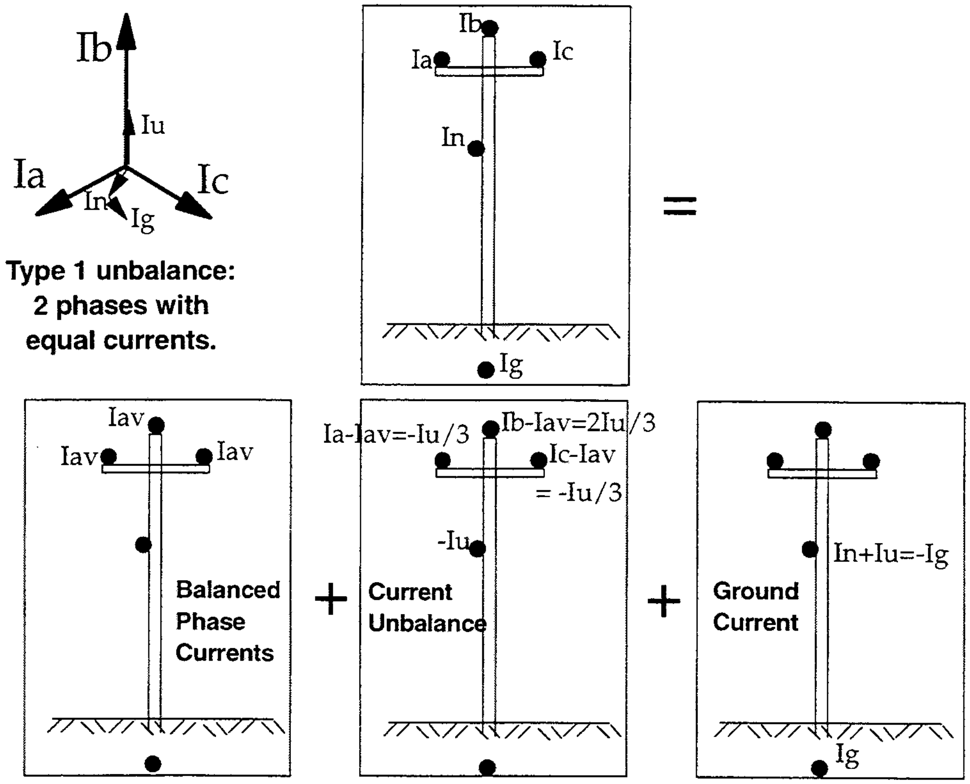

Figure 4-8 Decomposition of Currents into Balanced Phase Currents, Current Unbalance, and Ground Current. Unbalance Type 1

With type 1 unbalance, $I_a = I_c$, and the average phase current is:

$$I_{av} = \frac{2I_a + I_b}{3} \quad \text{(eq. 4-15)}$$

The current unbalance is the vectorial sum of the three phase currents. With type 1 unbalance, the current unbalance has the same phase as I_b and has a magnitude equal to:

$$I_u = \frac{3}{2}(I_b - I_{av}) = \frac{3}{2}UI_{av} \quad \text{(eq. 4-16)}$$

where U is the maximum deviation between a phase current and the average current divided by the average current: $U = \frac{I_b - I_{av}}{I_{av}}$

The phase currents can be decomposed in a system of balanced currents plus a system of unbalanced currents whose vectorial sum is equal to the unbalance. The neutral current can be considered as the opposite of the sum of the current unbalance and ground current. The system of currents can be decomposed as follows:

Table 4-2
Components of a system of distribution line currents in a 4 wire system. Unbalance type 1

Wire	Current	Balanced Component	Unbalanced Component	Ground Component
Phase A	$I_a =$	I_{av}	$-1/3\ I_u$	
Phase B	$I_b =$	I_{av}	$-1/3\ I_u + I_u = 2/3\ I_u$	
Phase C	$I_c =$	I_{av}	$-1/3\ I_u$	
Neutral	$I_n =$		$-I_u$	$-I_g$
Ground	$I_g =$			$+I_g$

The balanced component field is given by equation (4-9) [1].

The unbalanced component field has two parts, as suggested by Table 4-2. Combining these two parts we obtain:

$$B_u = \sqrt{B_{U1}^2 + B_{U2}^2} = \sqrt{\left(\frac{\sqrt{2}P_{abc}I_u/3}{R^2}\right)^2 + \left(\frac{2I_uP_{bn}}{R^2}\right)^2} = \frac{3UI_{av}}{R^2}\sqrt{\frac{1}{18}P_{abc}^2 + P_{bn}^2} \quad \text{(eq. 4-17)}$$

The ground component is:

$$B_g = \frac{2I_g}{R} = \frac{2GI_u}{R} = \frac{3GUI_{av}}{R} \quad \text{(eq. 4-18)}$$

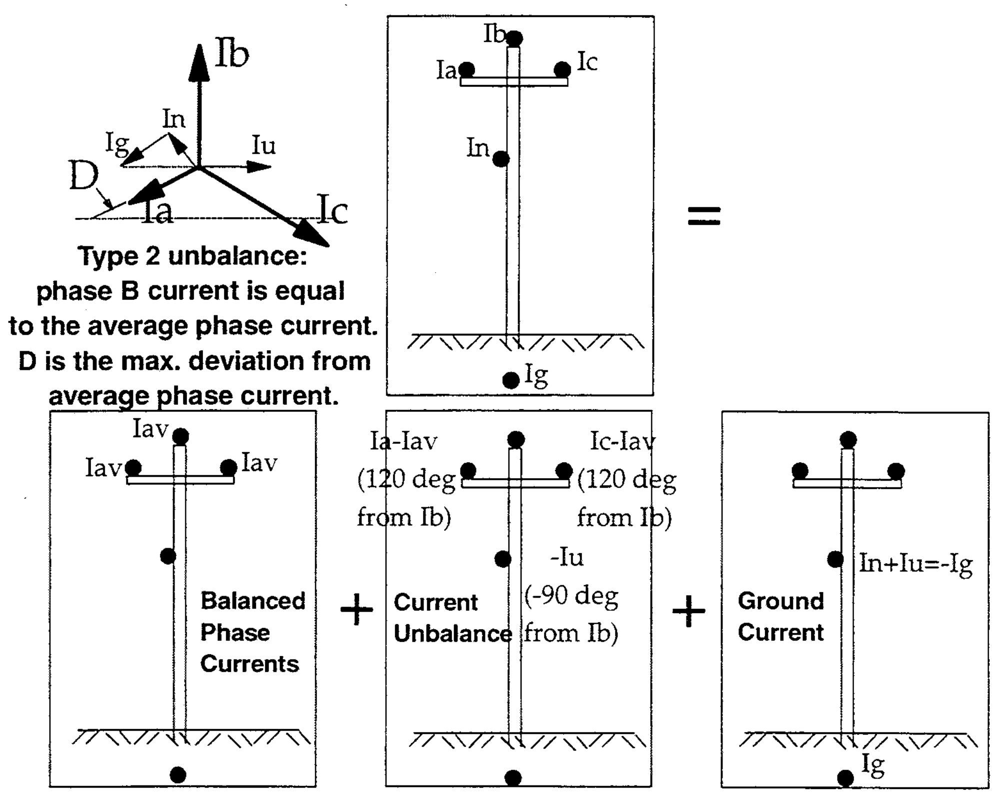

Figure 4-9 Decomposition of Currents into Balanced Phase Currents, Currents Unbalance, and Ground Current. Unbalance Type 2

With type 2 unbalance, $I_b = I_{av}$

The current unbalance is the vectorial sum of the three phase currents. With type 2 unbalance, the current unbalance has a phase angle of -90 degrees from I_b and has a magnitude equal to:

$$I_u = \sqrt{3}D = \sqrt{3}UI_{av} \qquad \text{(eq. 4-19)}$$

where D is the maximum deviation between a phase current and the average current.

The phase currents can be decomposed in a system of balanced currents plus a system of unbalanced currents whose vectorial sum is equal to the unbalance. The neutral current can be considered as the opposite of the sum of the current unbalance and ground current. The system of currents can be decomposed as follows:

Table 4-3
Components of a system of distribution line currents in a 4 wire system. Unbalance type 2

Wire	Current	Balanced Component	Unbalanced Component		Ground
Phase A	$I_a =$	I_{av} (phase = B + 120°)	$2UI_{av}/\sqrt{3}$ (phase = B-30°)	$Ui_{av}/\sqrt{3}$ (phase = B-150°)	
Phase B	$I_b =$	I_{av} (phase =B)			
Phase C	$I_c =$	I_{av} (phase = B - 120°)	$2Ui_{av}/\sqrt{3}$ (phase = B-150°)	$Ui_{av}/\sqrt{3}$ (phase = B-30°)	
Neutral	$I_n =$		$2UI_{av}/\sqrt{3}$ (phase = B+90°)	$Ui_{av}/\sqrt{3}$ (phase = B+90°)	$-I_g$
Ground	$I_g =$				$+I_g$

The balanced component field is given by equation (4-9) [1].

The unbalanced component field has two parts, a positive and a negative sequence of three phase currents, as suggested by Table 4-3. Combining these two parts we obtain:

$$B_u = \sqrt{B_{U+}^2 + B_{U-}^2} = \sqrt{\left(\frac{\sqrt{2}P_{acn}\frac{2}{\sqrt{3}}UI_{av}}{R^2}\right)^2 + \left(\frac{\sqrt{2}P_{acn}\frac{1}{\sqrt{3}}UI_{av}}{R^2}\right)^2} = \frac{\sqrt{10}UI_{av}P_{acn}}{\sqrt{3}R^2} \quad \text{(eq. 4-20)}$$

If type 2 unbalance is such that the phase with current equal to the average is phase A (or phase C), rather than B, equation 4-20 is still valid by substituting P_{bcu} (or P_{abu}) to P_{acu}.

The ground component is:

$$B_g = \frac{2I_g}{R} = \frac{2GI_u}{R} = \frac{2\sqrt{3}GUI_{av}}{R} \quad \text{(eq. 4-21)}$$

4.5 Calculation of Ground Currents Associated with a Distribution Line Secondary

4.5.1 The RESICALC Method

To characterize magnetic fields under complex load conditions, EPRI has developed software that models magnetic fields in residential neighborhoods. This program, named RESICALC, models the power-frequency magnetic field from any arbitrary user-specified array of neighborhood conductors, which may include transmission lines, one- two- or three-phase distribution primaries, secondaries and water mains. For residential service, the program models the grounding system including the pathway from the secondary neutral through the neutrals of the service drop and service cable to either or both ground rod and water service line and main. The user is provided default values for resistive and reactive impedance of all ground elements, but has the option of entering any custom value. The program runs in the Microsoft™ Windows™ operating environment 3.1 or higher.

To calculate ELF magnetic fields generated by current carrying conductors (in the absence of magnetic materials and conducting bodies in which significant eddy currents can be induced) it is necessary to know the conductor geometry and currents. This is done using the Biot-Savart law. In many practical cases, the conductor geometry can be determined with relatively good accuracy; the currents, however, are more difficult to specify. In a residential environment the currents that generate some of the largest magnetic fields [4] are the net currents in the service drops and the currents in ground connections and water pipes. These "ground currents" cannot be derived from the knowledge of residential load currents alone, because they depend also on the configuration and impedances of the electrical distribution network including ground conductors such as water pipes. RESICALC takes the circuit layout provided by the user, performs a network analysis, and calculates the ground currents given the loads at each residence.

RESICALC is based on sound engineering principles and has been verified experimentally at EPRI's Magnetic Field Research Facility in Lenox, MA (See Appendix B).

4.5.1.1 Biot-Savart Law

The Biot-Savart law has been applied to calculate the magnetic field in complex situations, such as substations [5, 6]. Application to a residential electrical network is also possible because the currents are confined to defined paths, i. e. wires and pipes.

RESICALC breaks the current paths into a number of straight current segments and uses the Biot-Savart law to calculate the field. This law is explained in several references [7, 8]. The final equations used to calculate the magnetic field are given in the following. The magnetic field vector, B, at a point P of coordinates (x_P, y_P, z_P), caused by a current, I, flowing in a conductor segment from (x_1, y_1, z_1) to (x_2, y_2, z_2) has the same phase as that of the current and a magnitude given by:

$$\overline{B} = B_x \overline{u_x} + B_y \overline{u_y} + B_z \overline{u_z} \qquad \text{(eq. 4-22)}$$

Where:

$\overline{u_x}$, $\overline{u_y}$, $\overline{u_z}$ are the unit vectors in the x, y, z directions

$$B_x = \frac{\mu_0 I}{2\pi l} K[(z_p - z_1)(y_2 - y_1) - (y_p - y_1)(z_2 - z_1)]$$

$$B_y = \frac{\mu_0 I}{2\pi l} K[(x_p - x_1)(z_2 - z_1) - (z_p - z_1)(x_2 - x_1)]$$

$$B_z = \frac{\mu_0 I}{2\pi l} K[(y_p - y_1)(x_2 - x_1) - (x_p - x_1)(y_2 - y_1)]$$

$$K = \frac{2l + C}{(4A^2 - C^2)\sqrt{l^2 + Cl + A^2}} - \frac{C}{A}$$

$$C = -2[(x_p - x_1)(x_2 - x_1) + (y_p - y_1)(y_2 - y_1) + (z_p - z_1)(z_2 - z_1)]$$

μ_0 is the permittivity of air, " l " is the length of the segment. A is the distance between P and the point 1 of the segment.

4.5.2 Calculation of the Currents in the Grounding System

The currents flowing into the grounding system of the residential distribution network are significant sources of residential magnetic fields [4] and can create local magnetic fields significantly higher than those from most power lines. These currents flow into wires that connect residential services to ground, water lines and water mains, and include the net currents in service drops.

Ground currents are generated by each residential load because of the grounding of the neutral at the residential service as shown in the typical configuration of Figure 4-8.

The load current, I_L, required by a 120 V appliance in house #1 is supplied by the transformer through the wires of the secondary and of the service drop. The load current returns to the transformer in a number of ways, because it splits at the service entrance, P. Part of the return current flows into the service drop neutral (I_N) and a part in the ground connection (I_G). The ground current then flows in the branches of the ground network: water lines, water main, ground rods, secondary neutral, the earth, and conductors of other utilities (telephone, cable TV) that are connected to the same grounds. The net current in the service drop, defined as the sum of the service drop wire, is equal to the ground current: $\tilde{I}_{NET} = \tilde{I}_L - \tilde{I}_N = \tilde{I}_G$.

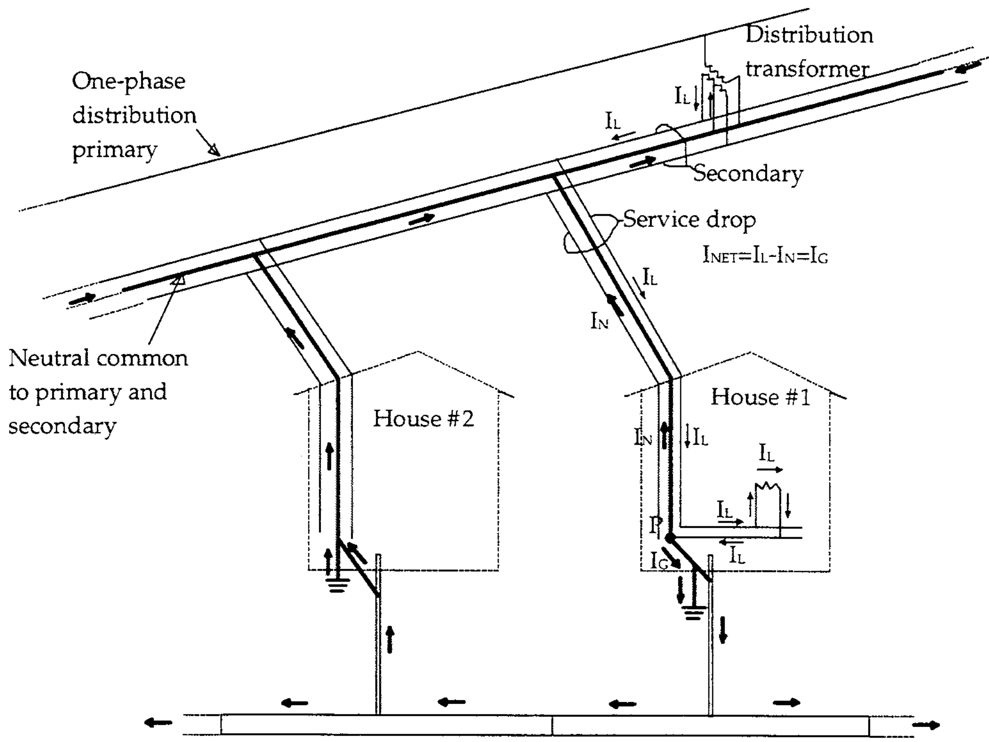

Figure 4-10 Ground currents caused by residential loads in a typical situation

RESICALC allows the user to draw and connect circuit elements on the computer monitor and sets up and solves the circuit equations [9]. The circuit parameters considered in the network analysis include resistances and self-inductances of electrical wires and water pipes, mutual inductances of closely spaced conductors and resistances of connections between different conductors that are part of the grounding circuit. The distributed leakage impedance of water pipes to ground is not considered in RESICALC models. However, it may be modeled using a lumped resistance to earth. RESICALC calculates the current in each branch of the ground network for each load. If there are 120 V loads derived from both legs of a service, or if there are 120 V loads applied to different homes, RESICALC calculates all the ground currents for each of these loads and adds the ground currents accounting for their magnitude and phase angle. For each load applied to each home RESICALC calculates the "ground current ratios", defined as:

$$\tilde{R}_{ij} = \tilde{I}_{Gi} / \tilde{I}_{Lj} \qquad \text{(eq. 4-23)}$$

where: $\tilde{I}_{Gi}$ is the ground current at the i_{th} home $\tilde{I}_{Lj}$ is the vectorial sum of the load currents of both legs at j_{th} residence.

The magnitude of the ground current ratio was measured during the 1000 home study [4]. Figure 4-10 provides a representative sample distribution of ground current ratios. For the large majority of residences the ground current ratio is near zero. Therefore, ground currents and ground current fields are not an issue in the majority of US residences. For many residences, however, the ground current ratio reaches significant values. For example, the ground current ratio exceeds 0.35 in 10% of the residences, and exceeds 0.5 in 4.5% of the residences. A ground current ratio of 0.5 means that every 120 V load of the residences causes a ground current equal to half of the load current. About 1% of the residences have a ground current ratio of about 1. This means that all the return current of house loads flows into the ground rather than in the service neutral.

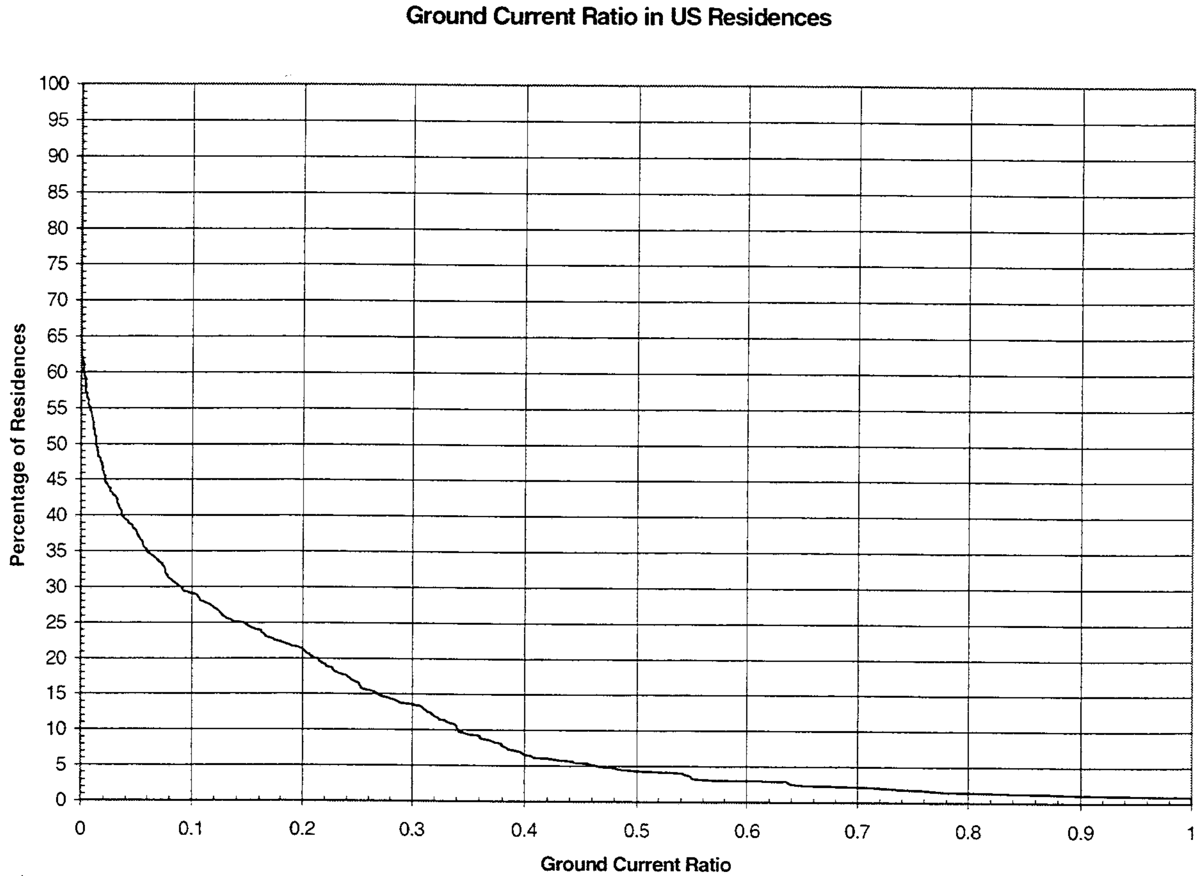

Figure 4-11 Ground Current Ratio in the US residences. Data from [4]

The total ground current $\tilde{I}_{GTi}$ at i_{th} home of a neighborhood of N_h homes is:

$$\tilde{I}_{GTi} = \sum_{j=1}^{Nh} \tilde{R}_{ij} \cdot \tilde{I}_{Lj} + \tilde{I}_0 \qquad \text{(eq. 4-24)}$$

where $\tilde{I}_0$ is the current caused by loads which are further away from the immediate neighborhood. The ground current ratios become smaller as the distance increases. Therefore, I_o is negligible in most practical cases and is ignored in RESICALC. Ground currents are not calculated for 240 V residential loads, which do not involve the service neutral.

Ground currents were systematically measured during the 1000 home study [4], which provides a representative sample of ground currents in US residences. The data are shown in Figure 4-11.

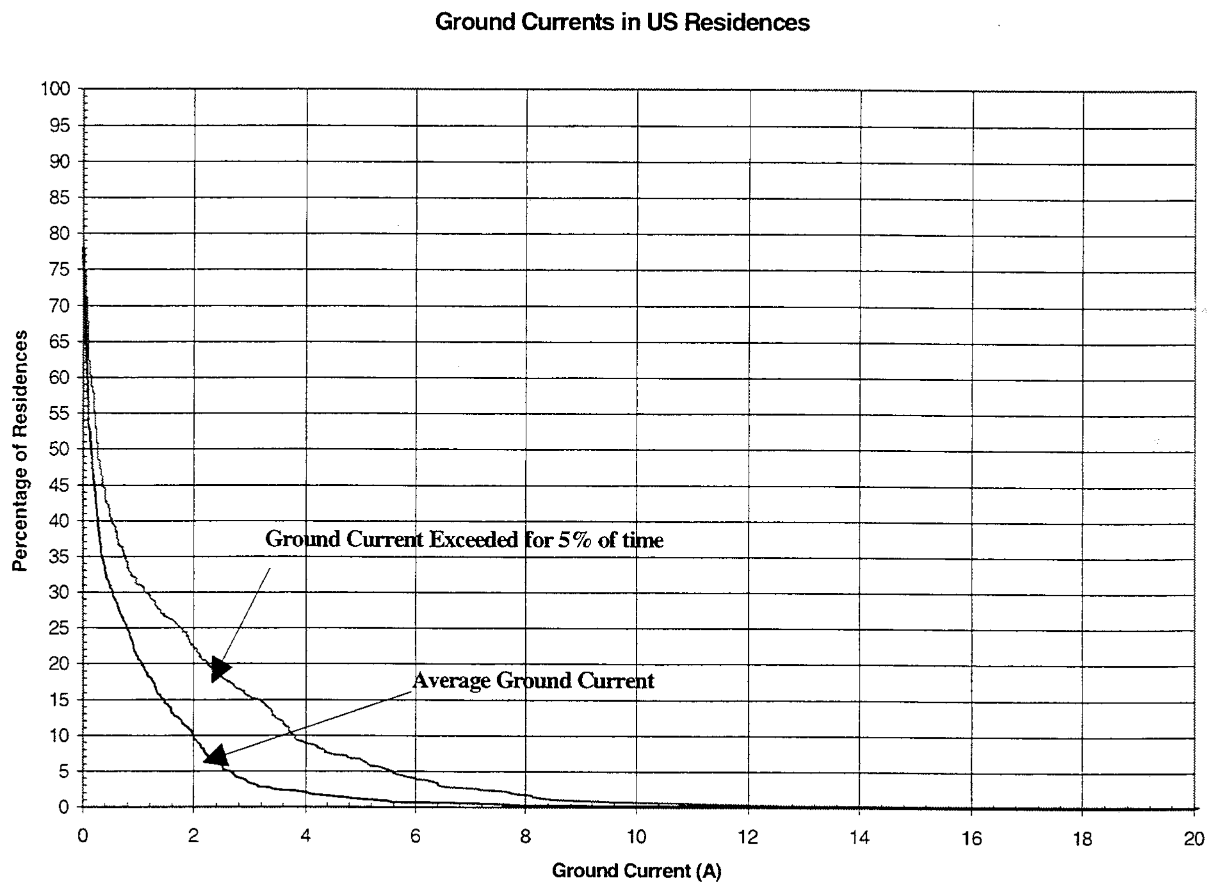

Figure 4-12 Ground Currents in US Residences. Data from [4]. Bottom curve, average 24-hour values. Upper curves, L5 values (values of ground currents exceeded for 5% of the 24-hour recording period)

The choice of electrical parameters for different types of conductors is facilitated by RESICALC through a menu from which specific conductors can be selected. The menu includes common types of distribution and residential wires and shows appropriate default values for resistance and GMD (Geometrical Mean Diameter). For three-wire service drops and for secondary wires the mutual distance d_m between the conductors are specified. For instance, for the neutral of a service drop cable made of several strands of copper wires wrapped around the two 120V wires and with an overall plastic jacket: R=0.8 mΩ/m, GMD = 1.25 cm, and d_m = 8 mm.

The values of GMD and d_m are used to calculate self and mutual inductances. The self inductance, L, of a conductor segment is given by:

$$L = 2 \cdot 10^{-7} l \; [\ln(\frac{4l}{GMD}) - 1] \qquad \text{(eq. 4-25)}$$

where l is the length of the segment; and the mutual inductance, M, between two parallel wires is given by:

$$M = 2 \cdot 10^{-7} l \; [\ln(\frac{l}{d_m} + \sqrt{1 + \frac{l^2}{{d_m}^2}}) - \sqrt{1 + \frac{{d_m}^2}{l^2}} + \frac{d_m}{l}] \qquad \text{(eq. 4-26)}$$

The values of GMD and d_m of several types of service drops and twisted secondaries were determined experimentally and are provided to the user in an appropriate menu.

4.5.3 Example of Calculation of Grounding System Currents

The method of ground current calculations was verified with several tests at the EPRI Magnetic Field Research Facility, which is described in Appendix 2. RESICALC software was exercised for a hypothetical neighborhood, using different scenarios to determine the effect of some design parameters on ground currents and the field they produce. The design parameters that were examined and their effect are shown in Table 4-4.

Table 4-4
Effect of Parameters on Ground Currents

Scenario (departure from base case)	**Effect on ground currents of individual houses**	**Effect on average ground currents of neighborhood**
Move transformer to one side of secondary	Ground currents are lowered for houses getting closer to the transformer and increased for houses getting further away.	Average neighborhood ground current increases slightly. (A few percentages)
Add one residence to the neighborhood	A small increase for each individual house.	Average neighborhood ground current increases slightly. (A few percentages)
Broken neutral at one house	A large increase in ground current of the house with the broken neutral. Ground current increases for some adjacent houses, decreases for some others.	Average neighborhood ground current increases.(10 - 30 %)
Dielectric insert in the water line of one house	Ground current is practically eliminated at the residence with the dielectric insert. Slight decreases in all the other houses.	Average neighborhood ground current decreases. (20 - 40 %)
Net Current Control (NCC) device in the service drop of one house	Ground current is practically eliminated at the residence with NCC device. Slight decreases in all the other houses.	Average neighborhood ground current decreases. (20 - 40 %)
Open bus secondary	Small, insignificant, increase in ground currents at all residences.	Average neighborhood ground current increases by an insignificant amount. (1 - 2 %)

The base case scenario, involving a neighborhood of six residences fed by the same secondary, with the distribution transformer in the center of the neighborhood and all houses connected to conductive plumbing, is shown in Figure 4-11. This figure shows the layout of the overhead secondary, service drops, service cables, grounding wires, water lines, and water main. All these elements comprise the "neighborhood grounding system".

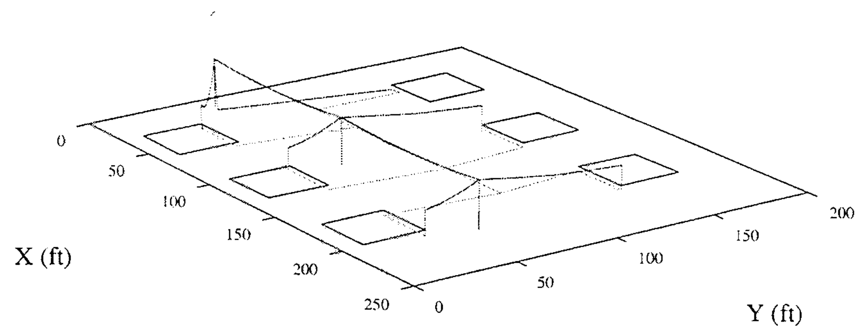

Figure 4-13 "Three Dimensional" perspective view of the layout of the grounding system of a six residence neighborhood

The parameters that characterize the different scenarios of Table 4-4 are discussed below.

Best location of the distribution transformer for low ground currents
In general, residences that are close to the distribution transformer have lower ground currents because the return path to the transformer is shorter through the neutral of the service drop than through the plumbing. The minimum value of the average ground current for all the residences connected to the same secondary is achieved when the <u>transformer is located in the geometric center of the electrical services</u>. This is also the location that minimizes distribution system losses.

Effect of adding residential services
Each additional residential service added to the secondary has two effects: (1) it reduces the impedance of the ground network and therefore increases the ground currents in the existing houses, and (2) it adds a source of ground currents. <u>An increase</u>

in the density of service, therefore, causes an increase in ground currents and residential magnetic fields. This is confirmed by the 1000 home study [4], which found a significant correlation between magnetic field and residence density, and between magnetic field and number of services for the same secondary.

Effect of a broken neutral

It is a rare but real occurrence that the service drop neutral loses some or all of its electrical continuity due to corrosion, mechanical fatigue, or other causes. In the 1000 home study, special measurements indicated 5 high impedance neutrals (broken or with a bad contact) out of about 700 homes for which these measurements were taken. A broken neutral causes all the return current of a house to return through the ground. The house with a broken neutral, therefore, will experience relatively high magnetic fields from ground currents. The situation for adjacent houses is more complex, with some houses experiencing more ground current (the ground current of the house with the broken neutral returns through adjacent houses), and some other houses experiencing less ground currents (the ground network impedance has increased and the ground currents generated by other houses is less). On average, the ground currents of the neighborhood are increased.

Dielectric insert in the water line

Interrupting the electrical continuity of the water line of a house has the effect of increasing the ground impedance enough to practically eliminate the ground current of that house. The electrical interruption can be achieved by placing a dielectric insert in the water pipe. This operation must be done in accordance with the National Electrical Safety Code and local safety codes. These codes may require that the water pipe not be interrupted for at least 10 feet from the point where it leaves the house, in order to provide a sufficiently low resistance ground. Interrupting the electrical continuity of the water pipe has also a beneficial, although minor, effect on the ground currents of neighboring residences.

Net Current Control device

The Net Current Control (NCC) device consists of a magnetic core around which all three wires (two 120 V wires and neutral) of the service drop are wound. Several prototypes developed by EPRI and Power Delivery Consultants were tested at EPRI's Magnetic Field Research Facility. An NCC prototype tested in 1995 consisted of eight turns of #2 AWG copper wire wound around a Finement iron core with an epoxy casing. The NCC device has six connection leads, three for the input and three for the output, allowing connection to a three-wire, single phase service drop cable. The NCC device encourages any load current to return in the service drop neutral and thus reduces the net current in the service drop. The flow of a net current magnetizes the core of the NCC device, inducing a voltage in each of the conductors opposing the flow of net current. This is equivalent to placing an impedance in the ground path. The performance of the NCC devices tested was such as to practically eliminate the ground current of the house on whose service drop the NCC was installed. Installing the NCC device at one residence has also a beneficial, although minor, effect on the ground currents of neighboring residences. The electrical schematic of the NCC device and the circuit on which it is installed is shown in Figure 4-12.

Tests have confirmed that the NCC device practically eliminates the net current $I_{net} = I_{load} - I_n = I_{ground}$. Under normal operating conditions the NCC device has a negligible voltage drop (about 0.6 V for every 10 A of load). The core is designed to saturate for large amounts of net currents so that no significant voltage drop occurs even if the neutral is interrupted.

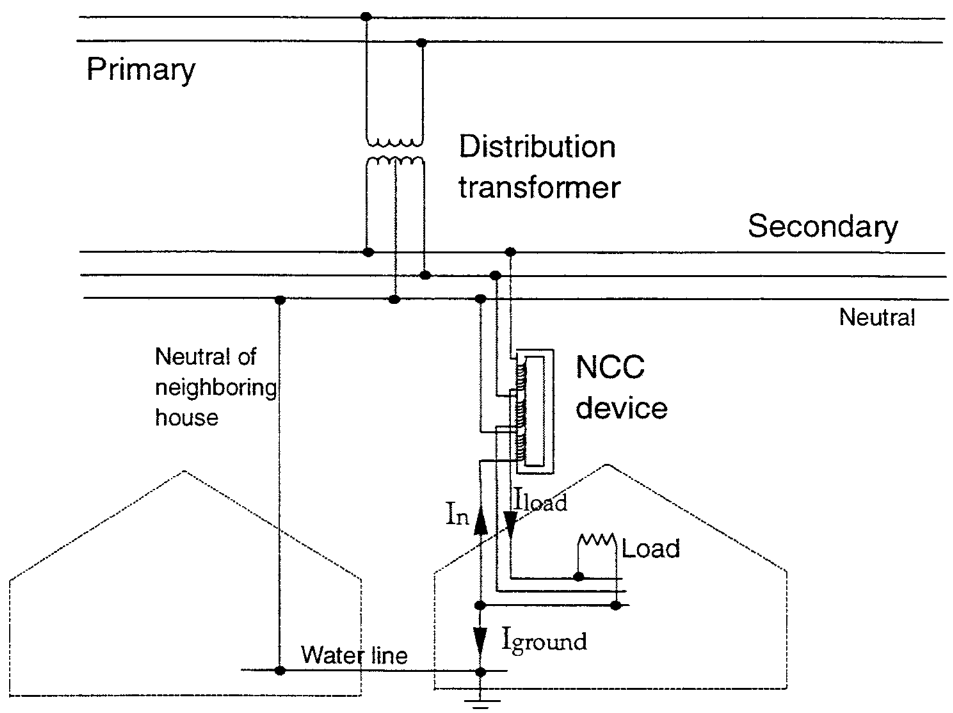

Figure 4-14 Schematic circuit showing a Net Current Control device inserted in the service drop of a residential service

Open bus versus spun secondary

A secondary in which the 120 V wires are twisted around the neutral, or are inside a shield acting as neutral, or are arranged so that the distance between the wires is as small as possible, corresponds to less ground currents than a secondary with the wires separated by a few inches or a few feet (open bus secondary). The reason for this behavior is the effect of the mutual inductance between the neutral and the 120 V wires. The larger the mutual inductance (i.e. the closer the wires) the greater the tendency of neutral current to be equal and opposite to the 120 V wire currents, thus reducing the net current. The principle is the same that prompted the design of the NCC device.

However, the effect is negligible. Ground currents are only marginally reduced passing from open bus to spun secondary. Spun secondary, however, has the advantage of reducing the magnetic field produced by the secondary balanced current. In fact, a spun secondary without net current produces negligible magnetic field, while open bus secondary may produce significant fields, especially if the separation between wires is a few feet and if secondary currents are high.

Installation of additional neutral wires

Ground currents are generated because the impedance of the ground path becomes comparable to that of the neutral path. Therefore, an effective method of ground current reduction consists of adding an additional neutral wire in parallel to each existing overhead secondary and service drop neutral. This type of installation may be advisable only in neighborhoods in which ground currents are a general and significant problem. The installation of additional neutral wires is very effective in reducing ground currents and also would have a (small) loss reduction effect. It would, in effect, be a competitive technique to the installation of NCC devices in a neighborhood where it is desirable to reduce ground currents.

Effect of the geometry of the grounding system

The magnetic field is determined by the value of the ground currents and by the geometry of the grounding system. For the same value of the ground current of a residence, the magnetic field depends greatly on how the grounding system is configured around the living space. The lowest magnetic field values are obtained for an underground service drop and a water line exiting near the entrance of the electric service. The magnetic field distribution in the living space of the first floor of the house (example with a 3 A ground current, field at one meter (3.28 feet) above the first floor, water pipes 3 feet below the first floor) is shown in Figure 4-13. Significantly higher magnetic field values are obtained for an overhead service drop and a water line exiting on a corner of the house away from the entrance of the electric service. The magnetic field distribution in the living space of the first floor of the house (example with a 3 A ground current, field at 3.28 feet above the first floor, water pipes 3 feet below the first floor) is shown in Figure 4-14.

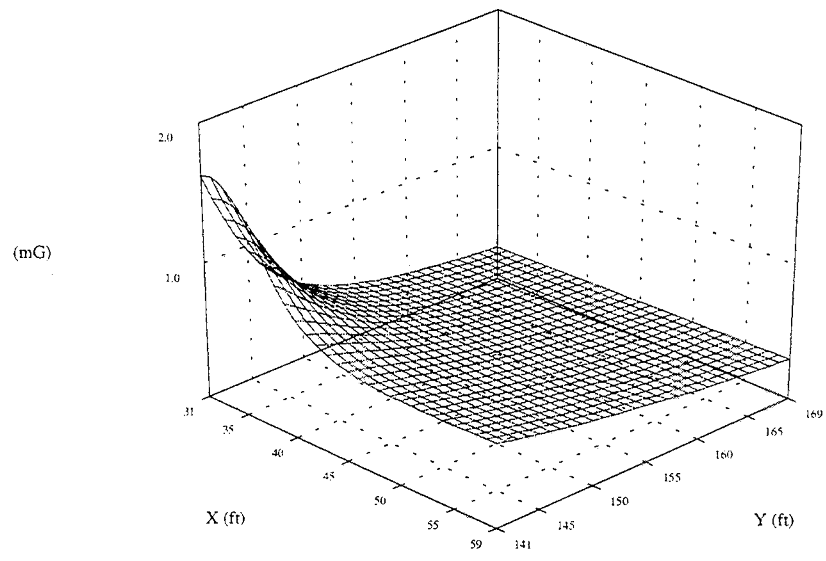

Figure 4-15 Magnetic field distribution in the living space of the first floor of the house with an underground service drop and a water line exiting near the entrance of the electric service. Example with a 3 A ground current, field at 3.28 feet above the first floor

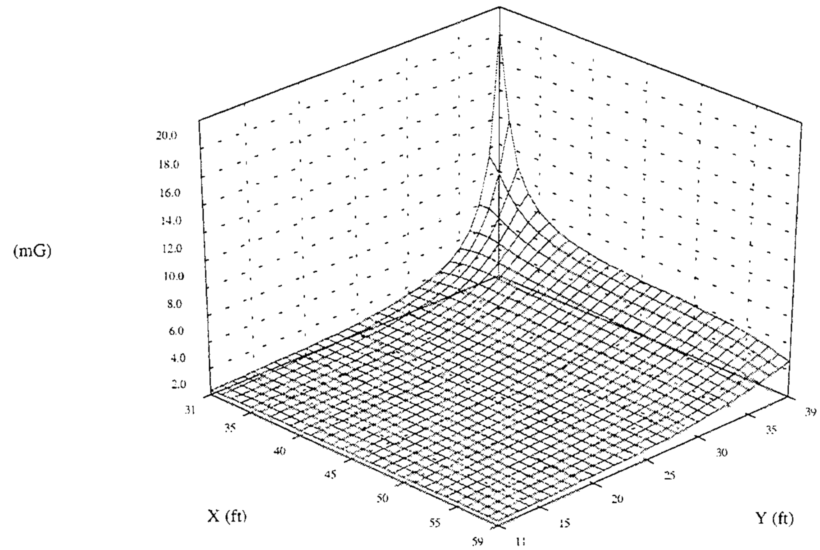

Figure 4-16 Magnetic field distribution in the living space of the first floor of the house with an overhead service drop and a water line exiting on a corner of the house away from the entrance of the electric service. Example with a 3 A ground current, field at 3 feet above the floor

4.6 References

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5

MEASUREMENTS OF DISTRIBUTION LINE MAGNETIC FIELD

5.1 Guidelines for Field Measurements

Several instruments and techniques are used to measure magnetic field from distribution lines. The instruments include hand held survey meters and microprocessor-based data loggers capable of storing a sequence of data which can be subsequently retrieved with a personal computer.

The measurement protocol should be such to provide repeatable results. A methodology applicable to power lines is described in IEEE Standard P644-1993 [1]. This standard was developed specifically for overhead transmission lines. However, most of its procedures apply to overhead distribution lines as well. The purpose of this standard is to establish uniform procedures for the measurement of power line fields and for the calibration of the meter used in these measurements. The main provisions of this standard are:

- *The magnetic field under power lines should be measured at a height of 1 m above ground level.* Although this recommendation is specifically made for overhead power lines, it is applied also for underground lines. However, it is important to note that magnetic field measurements are much more dependent on the height of the point of measurement above ground for underground than for overhead lines. Magnetic field exposure at ground level or at one meter above ground may not differ appreciably under an overhead line, but may be significantly different above underground lines. Consequently, the height above ground level should be accurately (within ± 5 cm) defined and measured for underground lines, while a greater tolerance (within ± 15 cm) may be accepted for field measurements under overhead lines.
- *The operator may stay close to the probe. Non-permanent objects containing magnetic materials or non magnetic conductors should be at least three times the largest dimension of the object away from the point of measurement in order to measure the unperturbed field value.*
- *The lateral profile of the magnetic field at points of interest along a span should be measured at selected intervals in a direction normal to the line at 1 m above the ground level.* Distances can be measured using a tape or a surveyor's wheel. Certain instruments have the capability of making lateral profile magnetic field and distance measurements simultaneously by placing a magnetic field recorder on the frame of a distance measuring wheel and adding to the recorder the provision to record the traveled distance.

- *The response of certain magnetic field meters is influenced by high levels of harmonic content. Therefore, if possible, the waveform of the field or its derivative (induced voltage) should be observed to obtain an estimate of the amount of harmonic content. A qualitative observation can be made with an oscilloscope. Replacement of the oscilloscope with a wave analyzer would permit measurements, in percent, of the various harmonic components. Note: The magnitude of harmonic components in the induced voltage (field derivative) are enhanced by the harmonic number.*
- *Measurement uncertainties due to calibration, temperature effects, etc, shall be combined (square root of the sum of the squares) and reported as total estimated measurement uncertainty. The total uncertainty should not exceed $\pm 10\%$.* Unfortunately, the greatest uncertainty about distribution line magnetic field is caused by the variability of line currents. To reduce this uncertainty, simultaneous measurement of line currents would be valuable so that magnetic field could be estimated for other values of line currents. However, distribution line currents are not usually known in all the details (magnitude and phase angle) necessary for an accurate calculation of magnetic field. Therefore, magnetic field estimates for situations other than that at the time of the measurements are subject to the type of uncertainty described in Section 4, even when current magnitudes are known.
- *Background information such as environmental conditions (for example, temperature, humidity), power line parameters (for example, line voltages and currents, conductor geometry, measurement location), and instrumentation used should be recorded.* The geometry of the conductors is described by their arrangement at the poles, by the conductor heights at the poles, and the conductor heights at mid-span. Lateral dimensions are generally given in utility drawings or specifications, and can be estimated with sufficient accuracy from the ground. Heights above ground can be measured with optical range finders or similar instruments. A photograph of the site is a useful document.

The required characteristics of the instruments for magnetic field measurements are described in an IEEE Standard [2]. This standard specifies methods that are needed to characterize instrumentation used to measure the rms values of magnetic fields with sinusoidal frequency content in the range 10 Hz to 3 kHz. This standard defines terminology, describes the general characteristics of magnetic fields, surveys the operational principles of instrumentation, indicates methods of calibration, and identifies significant sources of errors.

5.2 Measurements of Magnetic Field Temporal Variations

Magnetic field from distribution lines varies significantly in time. There are short term variations due to the random switching on and off of customer loads. In most cases there is a daily cycle with a minimum at night and one or two peaks during daytime. Some lines exhibit a weekly cycle with significant differences between weekdays and weekends. Finally, there is a seasonal cycle for those regions where the area load is dependent on season and weather conditions, which determine the extent of heating and lighting loads in the winter and air conditioning loads in the summer.

Twenty-four hour, once-a-minute recordings of distribution line magnetic field were measured at residences during EPRI's 1000 home study [3]. The magnetic field exceeded for less than 10% of the time (L_{10}) was greater than the median field (field exceeded for less than 50% of the time) by a factor K_{10} given in Table 5-1. The table reports also the factor K_5, applicable to L_5 (field exceeded for less than 5% of the time). Table 5-1 indicates, for example, that for 5% of the residences the temporal variations during a 24-hour period are such that the field for 10% of the time is greater than 2.6 times the median value and for 5% of the times is greater than 3.1 times the median value.

Table 5-1
Factors Characterizing the 24-Hour Temporal Distribution of Residential Fields Caused by Distribution Lines

	$K_{10} = L_{10}$ /Median	$K_5 = L_5$ /Median
Value exceeded in 95% of the residences	1.0	1.1
Value exceeded in 50% of the residences	1.5	1.7
Value exceeded in 5% of the residences	2.6	3.1

Typical 24 hour recordings of distribution line field measured inside residences are reported in reference [3], for different types of distribution lines: three phase lines with no net current (Figure 6-47 of reference [3]), single- or two-phase lines or secondary only with no net current (Figure 6-48 of reference [3]), underground distribution line with field caused by net current (Figure 6-49 of reference [3]), three phase lines with field predominantly caused by net current (Figure 6-50 of reference [3]), and single- or two-phase lines or secondary only with field predominantly caused by net current (Figure 6-51 of reference [3]).

Hourly average magnetic fields expressed in per unit of daily averages are shown in Figure 5-2 as a function of the time of the day. This figure shows the typical daily cycle, with the largest field values measured between 8 p.m. and 9 p.m., and the lowest field values measured between 4 a.m. and 5 a.m. For 50% of the residences, the distribution line magnetic field reaches an hourly average peak which is 20% (or more) greater than the daily average. During night time, on the other hand, 50% of the residences have a hourly average bottom value 20% (or more) lower than the daily average. Average night time (7 hours from 11 p.m. to 6 a.m.) residential field for 50% of the residences is 15% (or more) below daily average. Finally, the figure reveals that measurements taken during the 8 hours between 8 a.m. and 4 p.m. do not have any statistically significant deviation from the daily average. Therefore, this period of time is recommended for spot measurements of distribution line magnetic field.

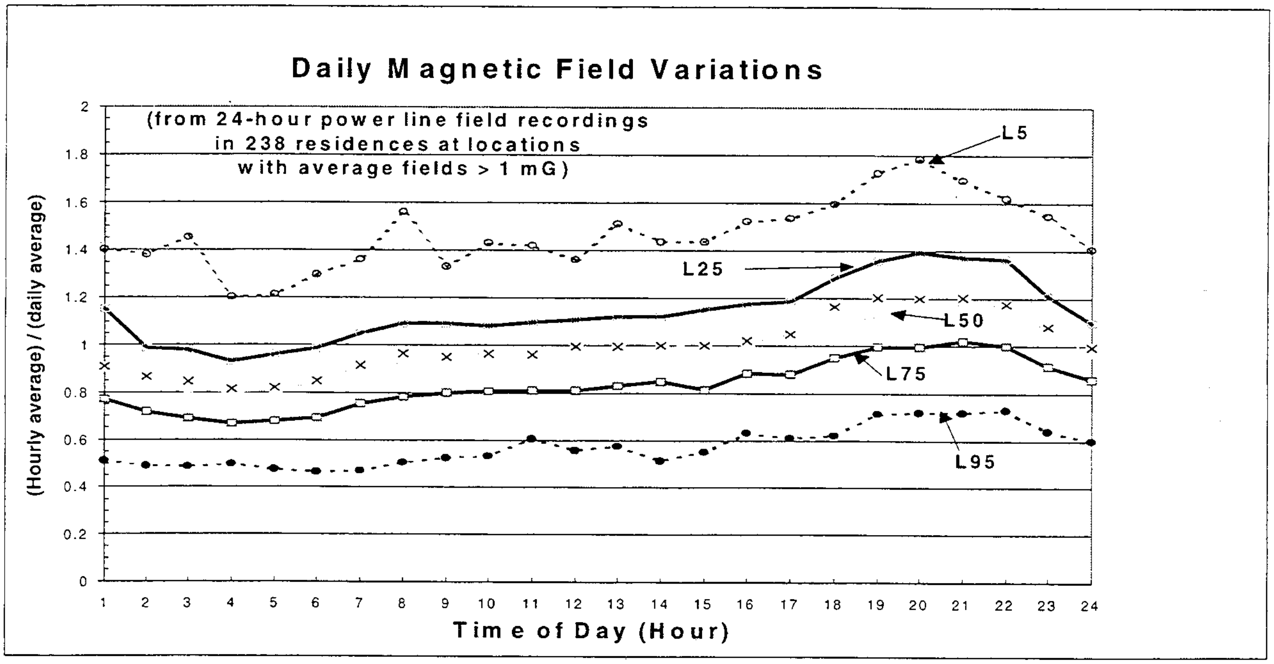

Figure 5-1 Hourly average magnetic field expressed in per unit of daily averages. The curves indicate values exceeded in 5, 25, 50, 75, and 95 % of the residences. Mean values are indicated by cross signs

Long term (more than 24 hours) distribution line magnetic field recordings require rugged field installations. For completeness, magnetic field recordings should be accompanied by current recordings. Current data can predict the temporal variations of magnetic field in first approximation only, because the field is not only a function of the average current of the distribution line, but also of the current unbalance and of the ground current, as discussed in Section 4. A representative set of current data can be derived from EPRI's Power Quality Node (PQN) project, whose relevance to distribution line magnetic field is discussed in Section 3. Long term temporal variations of the three different components of line currents and magnetic fields (balanced, unbalanced, and ground component) can be derived from the PQN database. Figure 5-2 shows an example of long term recording of average current, current unbalance, and ground current for a three-phase distribution line feeder. The values of the corresponding magnetic field components are a function of the line geometry (spacings between wires) and of the distance between line and measuring point. Equations that give magnetic field from line currents and geometry are shown in Section 4.

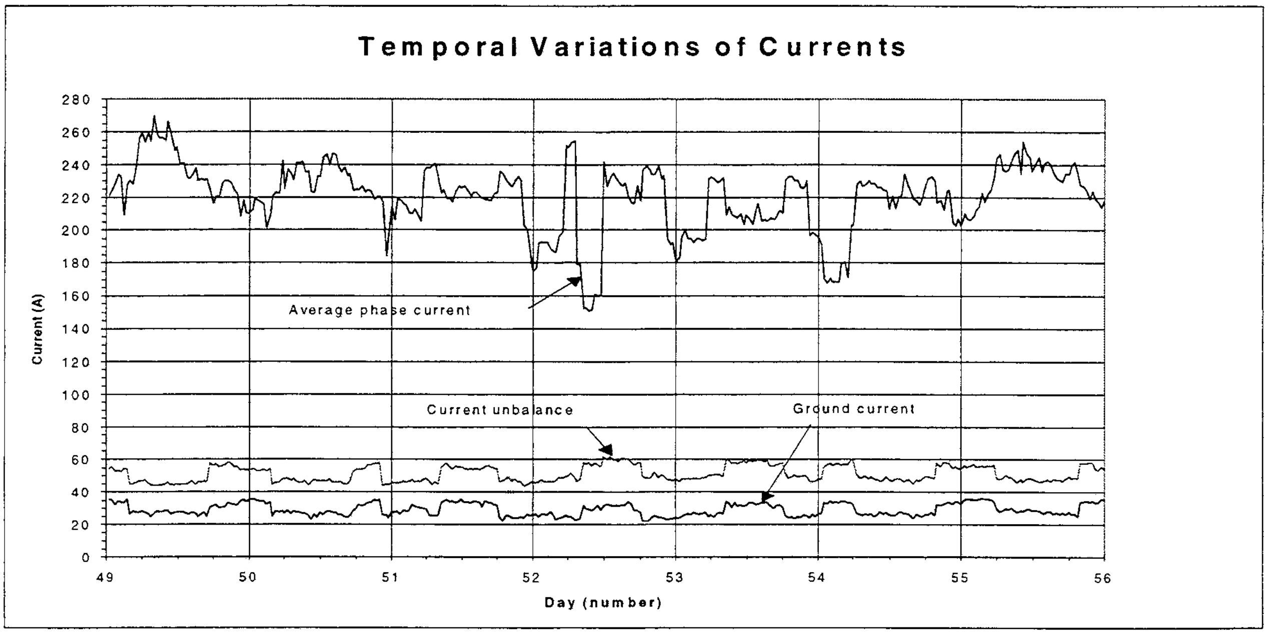

Figure 5-2 Temporal variations of currents (average phase current, unbalance, and net current)

5.3 References

1. "IEEE Standard Procedures for Measurement of Power frequency Electric and Magnetic Fields from AC Power Lines", American National Standard Institute, P644- December 1993.

2. "Recommended Practice for Instrumentation: Specifications for Magnetic Flux Density and Electric Field Strength Meters - 10 Hz to 3 kHz", IEEE Standard 644, 1994

3. "Survey of Residential Magnetic Field Sources. Volume 1: Goals, Results, and Conclusions" EPRI TR-102759-V1, September 1993.

6

TECHNIQUES FOR DISTRIBUTION LINE MAGNETIC FIELD REDUCTION

6.1 Magnetic Field Management

Magnetic field management of distribution lines presents two special challenges: the first is associated with the large societal cost of any overall change in the distribution system made to lower magnetic fields of existing installations and the second is related to the fact that different techniques are required to reduce the magnetic field caused by the balanced current, unbalanced current, and net current. On the other hand, reduction of magnetic field from distribution lines is likely to achieve an overall decrease in human exposure to magnetic fields significantly larger than that achievable by decreasing the field from most other sources. Engineering studies can give a case by case answer to the question of whether or not distribution line magnetic field reduction is cost effective in comparison to other magnetic field management measures.

Techniques for magnetic field management of 3-wire primary distribution lines have been only briefly presented in Section 4, while discussing the sensitivity of magnetic field to different line design parameters. These and other techniques are discussed in greater details below.

6.2 Overhead Three-Wire Primary Lines

As indicated in Section 4 the main field component is the balanced current component and the field can be approximated by equation (6-1).

$$B \approx \frac{\sqrt{2}\, P_{abc} I_{av}}{R^2} \qquad \text{(eq. 6-1)}$$

where: B is the field in mG

R is the distance between center of the line and measuring point in meter

$P_{abc} = \sqrt{P_{ab}^2 + P_{bc}^2 + P_{ca}^2}$ is the equivalent phase spacing (in meter) derived from the spacings between the different phases.

$I_{av} = (I_a + I_b + I_c)/3$ is the average current in ampere.

Equation (6-1) suggests ways to reduce the magnetic field: reduce the value of P_{abc}, reduce I_{av}, or increase R.

6.2.1 Phase Compaction

The value of P_{abc} can be reduced by modifying the line geometry. The line geometry that produces the highest magnetic fields is the cross arm configuration. Different techniques that may be applied to reduce the field of this configuration are shown in Figure 6-1.

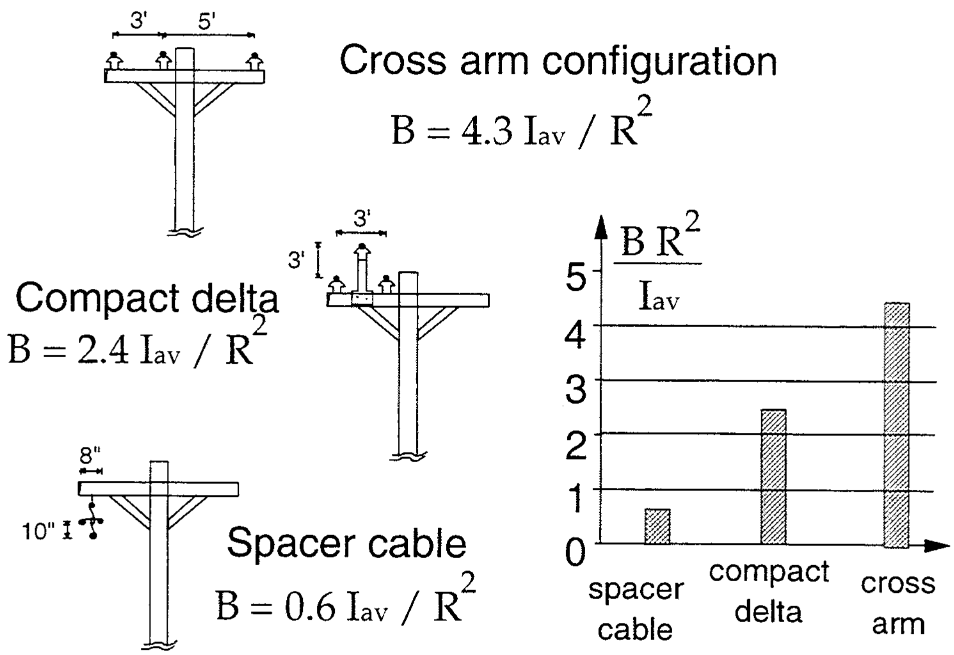

Figure 6-1 Modification of cross arm configuration to reduce the magnetic field of three-wire primary distribution lines and the balanced component of the magnetic field of four-wire primary distribution lines

For new construction of 3-wire primary distribution lines in areas where magnetic field is a concern, the spacer cable arrangement is recommended. In areas where spacer cables are not desirable for reasons of cost, aesthetics, UV damage, or are against utility practices for some other reason, compact configurations of different types may be used to obtain low fields. The degree of available compaction depends little on the basic insulation level, BIL, and more on the span length and expected wind and ice conditions. Examples of compact line designs are shown in Figure 6-2.

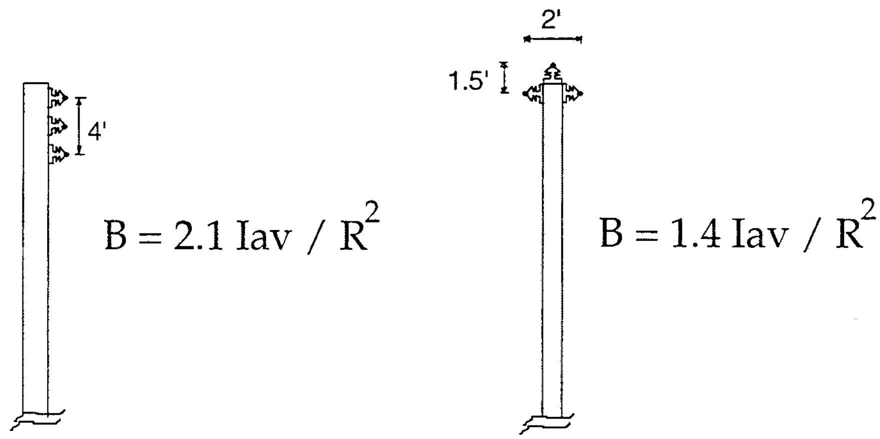

Figure 6-2 Compact 3-wire primary distribution line design for low magnetic field

6.2.2 Reducing Line Current by Increasing the Line Voltage

According to equation (6-1) the magnetic field is directly proportional to the average line current. The line current can be reduced and the line can carry the same amount of power if the line voltage is increased in the same proportion. For instance, an increase in line voltage by a factor of 3 implies a reduction in line current and in magnetic field by a factor of 3.

Increasing line voltage involves changing the transformer that feeds the line at the substation, all the transformers that bring power to the customers, and most likely all the insulators that support the conductors. The cost of this changes may be partially offset by a reduction of loss (RI^2 loss).

Several distribution line voltages are in use in the United states as indicated in Table 6-1 [1].

Table 6-1
Standard Nominal Primary Distribution Voltages

Three-wire (voltage) (phase - phase)	Four-wire (voltage) (phase - phase/phase - ground)
2400	
4160	4160Y/2400
4800	
6900	
	8320Y/4800
	12000Y/6930
	12470Y/7200
	13200Y/7620
13800	13800Y/7970
	20780Y/12000
23000	22860Y/13200
	24940Y/14400
34500	34500Y/19920

6.2.3 Increasing the Distance to Measuring Point by Increasing Line Height

Equation (6-1) indicates that the magnetic field of 3-wire primary distribution lines is inversely proportional to the square of the distance between the center of the three wires and the measuring point. When the measuring point is near the ground level, an increase in distance, R, can be achieved by increasing the line height, as indicated in Figure 6-3. The effect of line height diminishes with an increase in the lateral distance between the line and the measuring point.

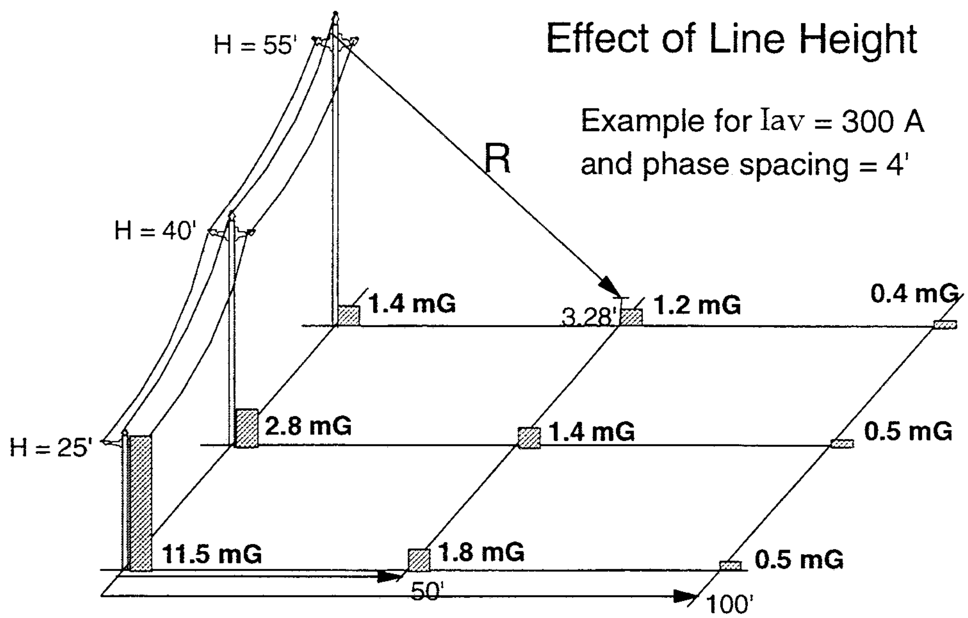

Figure 6-3 Reduction of the magnetic field of a 3-wire primary distribution line and of the balanced component of a 4-wire primary distribution line by increasing line height

The effect of the combination of line compaction and increase in line height is shown in Figure 6-4 for the field at 1 meter above ground both directly underneath the wires and at 25 feet horizontally from the line.

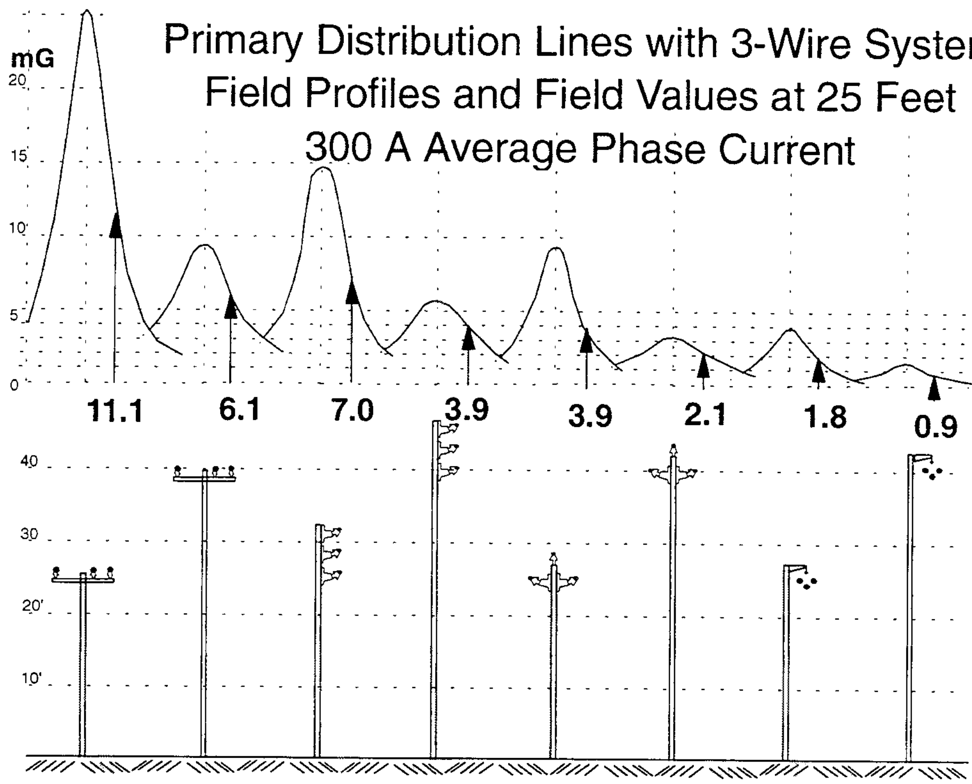

Figure 6-4 Examples of lateral profiles of magnetic field for different types of 3-phase, 3-wire primary distribution lines

6.3 Overhead Four-Wire Primary Lines

In Section 4, it is shown that four-wire primary lines (3-phase wires plus a neutral) have three magnetic field components: "balanced", "unbalanced", and "ground" field components. In some situations the balanced component predominates, while in some others the ground component predominates. The unbalanced component is rarely predominant.

6.3.1 Balanced Component

The field reduction techniques discussed for three-wire distribution lines apply to the balanced component of four-wire distribution lines as well. These techniques include: compact delta, spacer cable, compact vertical arrangement, increasing line voltage, and increasing line height.

6.3.2 Ground Component

Changing the configuration from horizontal cross arm to delta, or compacting the line geometry are ineffective techniques for reducing the ground component of the magnetic field. The ground component of the field, B_g, is given by equations (4-11) or (4-13) that can be written as:

$$B_g = k\frac{GUI_{av}}{R} \qquad \text{(eq. 6-2)}$$

where k is a coefficient of proportionality.

Equation (6-2) shows that reducing the current by increasing the voltage is as effective as previously discussed for three-wire lines and for the balanced component of four-wire lines.

Increasing the distance, R, however, is not as effective because the ground component does not decrease as rapidly as the balanced component.

6.3.2.1 Balancing the 3-Phase Currents

The ground component is proportional to the product of the unbalance, U, and the ground current ratio, R. Therefore, it appears that reducing U by balancing the line current is a very effective method of reducing B_g. This assumes that G and U are independent. This is generally true when the neutral does not carry any unbalance of other distribution lines and the neutral of other lines do not carry any unbalance of the line. This situation occurs for the radial feeder illustrated in Figure 6-5. The currents flowing through the section S of the line are balanced when the loads on each phase are equal. The sum of the currents in the neutral and in the ground at location S is then equal to zero. In general, this situation corresponds to zero current in the neutral. However, the neutral current may be different from zero, if the neutral-to-ground impedances of the laterals are not equal. In this case, the neutral return current of a lateral may be different from the return currents of the laterals of other phases and give rise to a total neutral current at location S, despite the fact that the unbalance is zero. In fact, for a zero ground current, not only the phase currents but also the ground impedances of the laterals must be balanced. A non-zero neutral current may exist in a balanced current situation if, for instance, the lateral connected to one of the phases has residential services grounded at conductive water pipes, while the laterals of the other two phases are in streets with plastic water pipes.

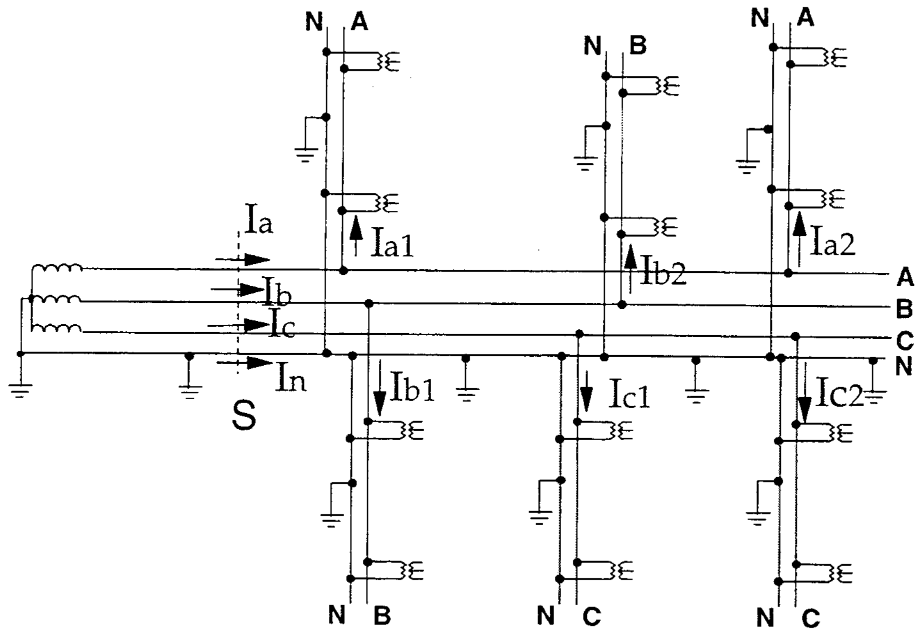

Figure 6-5 Phase currents in a radial feeder resulting from the sum of single phase currents in "laterals"

6.3.2.2 Increasing the Size of the Neutral

A way of reducing the ground component of the field is to make the neutral the lowest possible impedance path and, conversely, the ground the highest possible impedance path.

Increasing the size of the neutral decreases the neutral impedance. For instance, a neutral of size 1/0 ACSR with current return at a mean distance of 6 feet has an impedance Z1=0.9+j0.8 ohm/mile, while a neutral of size 4/0 ACSR has an impedance Z2=0.4+j0.7 ohm/mile. If the ground return paths have impedances significantly higher than the neutral return path, the ground return current will be reduced approximately in the proportion Z1/Z2 = 1.5. If the ground component of the field must be reduced in an existing situation, the neutral impedance may be reduced by adding an additional wire in parallel to the existing neutral and placing it at a considerable distance (2 ~ 3 feet) from the existing wire. The large spacing between neutrals is required to reduce the reactance as much as possible, since the reactance is generally a significant component of the impedance. For instance doubling a neutral of size S1 by adding a wire of the same size at a distance of 2 feet reduces the impedance from 0.9+j0.8 ohm/mile to 0.45+j0.45 ohm/mile, which is a factor of about 2.

6.3.2.3 Increasing the resistance of the neutral grounds

Increasing the resistance of the neutral grounds is effective in reducing ground currents. This is difficult to accomplish, especially in existing situations. It requires disconnecting service grounds from a metallic water system, or isolating primary and secondary neutrals, or using a 5-wire primary system. Isolation of primary and secondary neutrals is discussed in Section 6.4. The 5-wire primary system is discussed in Section 6.5.

6.4 Isolating Primary and Secondary Neutral

Residential service grounds are the largest contributors to a low primary-to-ground impedance [2, 3]. Therefore, isolating primary neutrals from secondary neutrals achieves the purpose of increasing the resistance of the primary neutral to ground.

Neutral Isolation (NI) devices are used on distribution lines to isolate the primary and secondary neutrals at the distribution transformer [4]. The use of these devices is allowed under Article 250-21, "Objectionable Currents Over Grounding Conductors", of the National Electrical Code (NEC). Under this article, alterations can be made to the grounding conductor to stop the flow of objectionable current, and included among the options for solving the problem is the interruption of the conductor or conductive path interconnecting common ground connections.

NI devices have been used at service points on farms to block stray neutral-to-earth currents [5]. Section 97 D of the National Electric Safety Code (NESC), which regulates installation of these devices on distribution lines, requires that the devices have a 60 Hz breakdown voltage not exceeding 3 kV. In addition, the code requires that a secondary grounding electrode be provided not less than 6 feet from the primary neutral grounding electrode.

There are different types of NI devices: the saturable reactor, the solid state switch, and the spark gap. Although these three devices are based on different operating principles, they all have similar characteristics: they provide a high impedance below a specified threshold voltage and a low impedance when the voltage exceeds the threshold. The major concern with the use of these devices is their ability to allow passage of sufficient fault current to permit primary overcurrent devices to operate correctly and ensure customer protection.

All three types of NI devices were investigated at the EPRI Magnetic Field Research Facility (described in Appendix B) as a method of blocking neutral-to-earth currents and their associated magnetic fields.

The NI devices are inserted in the distribution system as shown in Figure 6-6.

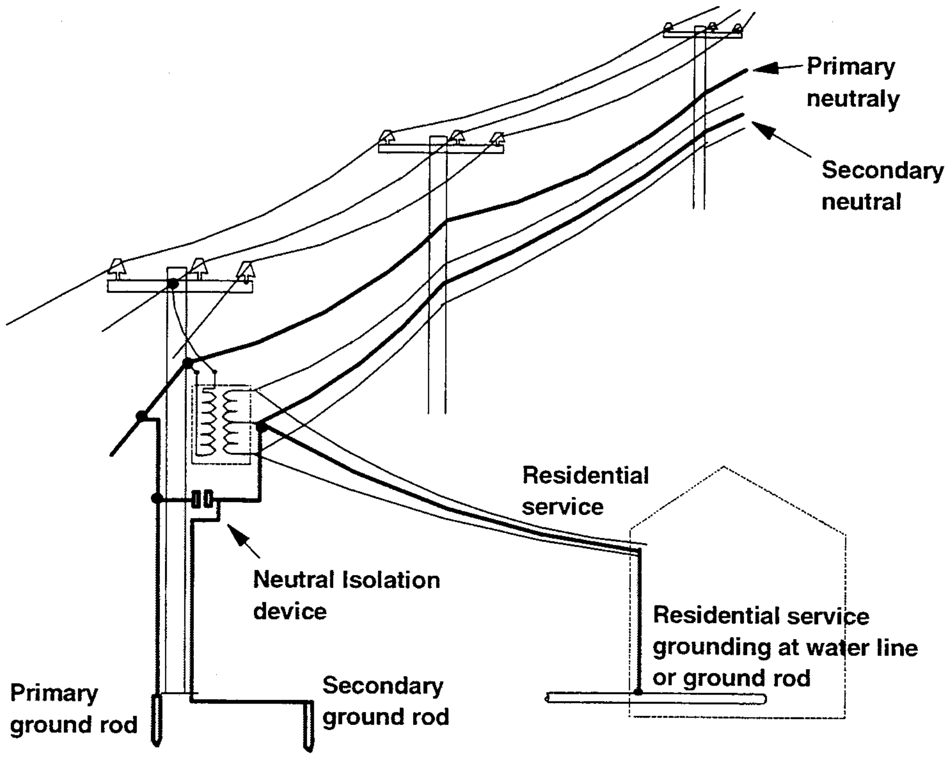

Figure 6-6 Location of neutral isolation device on the distribution system to reduce ground currents

Saturable Reactor. A saturable reactor is designed to provide a high impedance to a voltage across the device that is below the "blocking voltage", which for this application is about 10 V. At voltages below the blocking voltage, the reactor current does not exceeds a few milliamperes. The impedance of one of the tested reactors was about 2000 ohm. For voltages greater than the blocking voltage, the impedance drops and the device effectively connects the neutrals. The saturable reactor is also equipped with a surge arrester to divert fast rising transients and prevent high voltages from developing across the reactor.

Solid-State Switch. A solid-state switch is designed to provide a high impedance to a voltage across the device below the "60 Hz switching threshold voltage" (a typical value is about 30 V rms). Below the threshold voltage the switch current does not exceed a few milliamperes. The impedance of a tested solid-state switch varied from 12,000 ohm below 12 V to 3,000 ohm just below the threshold of 30 V. At the threshold voltage a control circuit within the device fires a thyristor, which puts the device in a low impedance state until the differential voltage across the device reaches zero. A surge arrester is in parallel with the thyristor to divert fast-rising transients.

Spark Gap. A type of spark gap that may be considered for the purpose of isolating primary from secondary neutrals is a gas tube with a DC sparkover voltage of about 750 V. Such spark gap consists of a metal bottle filled with an inert gas in which there are two closely spaced electrodes. At a specified threshold voltage the gap breaks down, allowing current to flow through the device. Below the threshold voltage there is no measurable leakage current, thus making the impedance of this device much larger than that of saturable reactors and solid-state switches.

6.5 Five-Wire Primary Lines

A method that practically eliminates ground currents associated with primary distribution lines and still maintains the advantages of a four-wire multi-grounded system, is the five-wire system, shown in Figure 6-7.

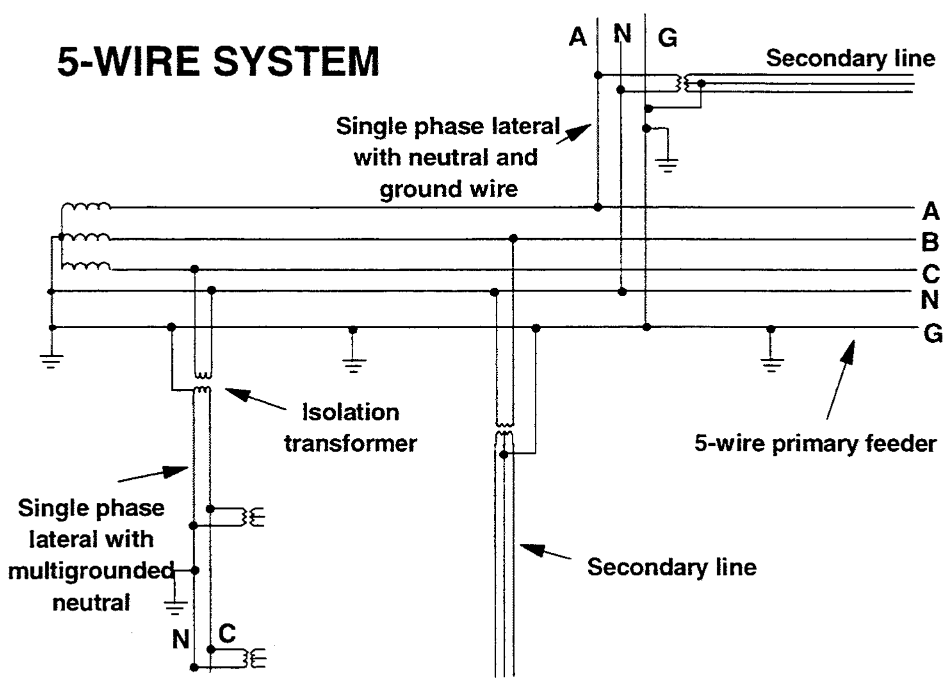

Figure 6-7 Five-wire primary distribution system

The five-wire system shown in Figure 6-7 has a "ground wire" in addition to the neutral. The ground wire is connected to distribution transformer tanks, secondary neutrals, and to neutrals of single phase laterals. The ground wire is not connected to the primary neutral of any transformer connected to the three phase feeder.

Single phase laterals may still have multi-grounded neutrals. However, this requires the isolation of the neutral of the three phase feeder from the neutral of the single phase laterals (see Figure 6-7). If isolating transformers are not used, both neutral and ground wires must be carried along the lateral (see Figure 6-7).

The ground wire does not carry current during normal operation and the net current of the distribution line is zero. All the unbalance is carried by the neutral and there is no current in the ground associated with the three-phase feeder.

In order to assure that the net current of the three-phase feeder is zero, the neutral of the feeder cannot be connected to the neutral of any other feeder.

6.6 Reduction of Magnetic Field from Overhead Secondary and Service Drops

Secondary and service drops generally consist of three wires: two wires at a nominal voltage 120 V and a neutral at ground potential. The nominal voltage between the 120 V wires is 240 V. These voltages are provided by the low voltage winding of distribution transformers.

An overhead secondary line supplies one or more services. The EPRI 1000 home study [6] found that the median number of services for the same secondary was 7. In 5% of the cases, however, the secondary supplied one residence only, and in another 5% of the cases there were more than 20 residential services for the same secondary.

Generally, an overhead secondary line is supplied by one distribution transformer only. In some cases, however two or more transformers are "banked" on the same secondary and share in providing single phase to the residences. Banked transformers were present in about 10% of the residences surveyed [6].

Overhead secondary and service drops may be of the open wire type or the triplex type, in which the two 120 V wires are wounded around the neutral. The triplex type produces much lower fields than the open wire type. If the secondary or the service drop have no net current, the field produced by the triplex type is practically zero, except in very close proximity (a few inches) of the wires.

For the purpose of calculating the magnetic field of a secondary, it is useful to separate the currents into two components: a balanced system of currents and the net current. The balanced system consists of the currents in the two 120 V wires and their return current is assumed to be in the neutral. If I_1 and I_2 are the currents in the two 120 V wires, and I_n is the current in the neutral, the two component systems of currents are:

Balanced system of currents: $\overline{I_1}$, $\overline{I_2}$, $,\overline{I_u} = -\left(\overline{I_1} + \overline{I_2}\right)$

(Note that the sum of the three currents is equal to zero)

Net current (residing in the neutral): $\overline{I_{net}} = \overline{I_1} + \overline{I_2} + \overline{I_n} = \overline{I_n} - \overline{I_u}$

The balanced system of currents produces a field that depends on how the currents are distributed among the wires and on the geometry of the wires. If the spacing between the two 120 V wires is P and the neutral current is small in comparison to the average current: $I_{av} = (I_1 + I_2)/2$ in the 120 V wires, the magnetic field at a distance R is:

$$B = \frac{2PI_{av}}{R^2} \qquad \text{(eq. 6-3)}$$

where B is expressed in mG, P and R in meter, and the current in ampere.

It is obvious that, since the distance R and the current cannot be easily changed, the most effective method of field reduction is reducing the spacing P. The spacing between secondary wires can be reduced to just a little more than the wire diameter because the wires are insulated for 120 V. Triplex type secondary has extremely small phase spacing, P, and the balanced component practically does not produce magnetic field.

The net current component of the secondary is caused by ground currents as discussed in Section 4.

6.7 Reduction of Residential Fields Caused by Ground Currents

The method of calculating residential ground currents and the associated magnetic field was discussed in Section 4. Section 4 also discussed some magnetic field management techniques suggested by the results of ground current and field calculations. The suggested techniques are:

- The best location of the distribution transformer is the geometric center of the electrical services.
- An increase in the density of services connected to the same metallic water pipe network causes an increase in ground currents and residential magnetic fields. Any residential service ground disconnection from the water pipe network decreases the magnetic field.
- A broken or high impedance service drop neutral may cause significantly higher than average magnetic fields at the served residence. A program of locating and repairing broken or high impedance neutrals would be effective in residential magnetic field exposure reduction.

- Placing a dielectric insert in the water pipe practically eliminates the ground current magnetic field of a house and has also a beneficial, although minor, effect on the ground currents of neighboring residences.
- Inserting a Net Current Control device on the utility side of the service drop is effective in reducing the ground current of a house.
- Using triplex rather than open bus type secondary and service drops not only reduces the field caused by balanced currents but also has a small but beneficial effect in reducing the ground currents.
- An effective method of ground current reduction consists of adding an additional neutral wire in parallel to each existing overhead secondary and service drop neutral.
- The magnetic field depends greatly on how the grounding system is configured around the living space. The lowest magnetic field values are obtained for an underground service drop and a water line exiting near the entrance of the electric service.

An additional method for reducing residential fields caused by ground currents is to divert the ground current away from the grounding system of the residence. This technique, first proposed by Edward Leeper [7] was verified with tests at EPRI's Magnetic Field Research Facility (described in Appendix B). The technique is illustrated in Figure 6-8. The portion of the service drop, ground wire, and water line that carry a net current or a ground current that produces magnetic field in a residence are placed in steel conduits. A conductor is placed inside the conduit and arranged to form a loop which is placed away from the areas of the residence where the field reduction is desired. The loop conductor can be connected to the conduits and to the water line but should be isolated from the service neutral. Any net current, I_g, in the grounding system formed by service drop, grounding wire, and water line will induce an opposing current, I_c, in the loop wire. The induced current, I_c can reach values approaching those of I_g, thus providing an effective cancellation of the field in the areas of the residence adjacent to service drop, grounding wire, and water line. The current I_c, however, causes a magnetic field in the areas where the conductor forming the loop is placed. In effect, the ground current is diverted to less sensitive areas.

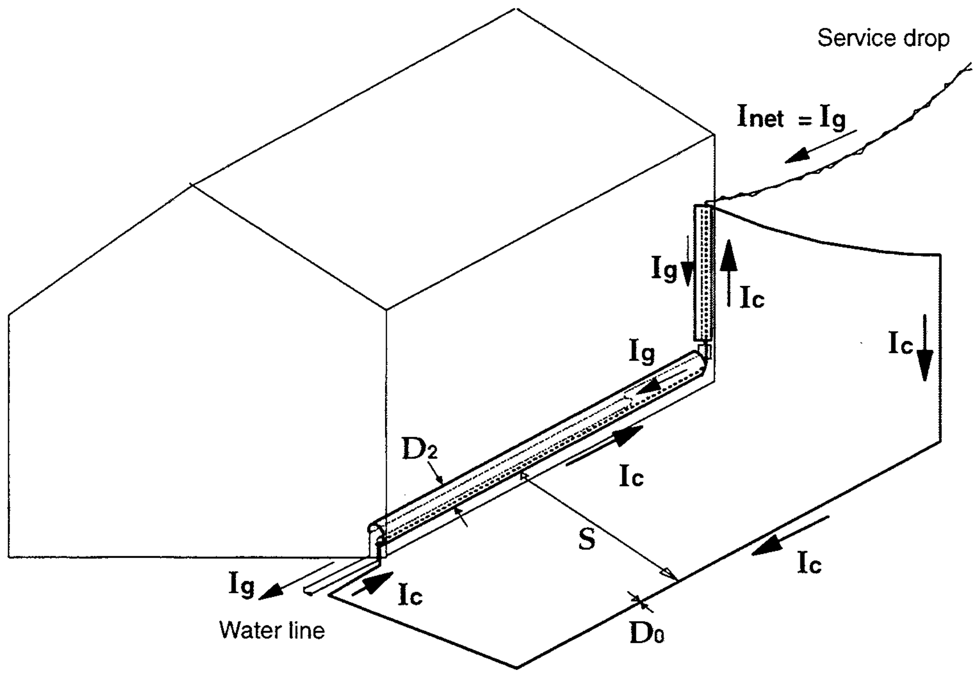

Figure 6-8 Diversion of a portion of ground current using a loop formed by a conductor connected to steel conduits placed around the grounding system of a residence

The method illustrated in Figure 6-8 was verified experimentally with tests on various arrangements of conduits and conductors. The following observations were made:

- The best arrangement is obtained when the conduit is made of high permeability material: galvanized steel conduits perform better than aluminum or copper conduits.
- Smaller diameter and thicker wall pipes perform better than larger and thinner pipes.
- The grounding system section covered with conduit should be as long as the length of the loops allows.
- The best results are obtained when the loop conductor resistance is as small as possible.
- The best results are obtained with the smallest possible loop size.

The experimental observations support the view that the steel conduit increase both the mutual impedance between ground current and cancellation loop and the self impedance of the cancellation loop.

The mutual impedance between the ground current and the loop is given by:

$$Z_{gc} = j\omega M_{gc} = j\omega \frac{\mu_0 \left(\mu_r \ln \frac{D_2}{D_1} + \ln \frac{S}{D_2} \right)}{2\pi} \qquad \text{(eq. 6-4)}$$

where D_1 is the inner diameter of the steel conduit, D_2 is the outer diameter of the steel conduit, S is the separation between the steel conduit and the return wire of the loop, μ_0 is the permeability of air, and μ_r is the relative permeability of the steel conduit.

The self impedance of the loop is:

$$Z_c = 2R_c + j\omega M_c = 2R_c + j\omega \frac{\mu_0 (\mu_r - 1) \ln \frac{D_2}{D_1}}{2\pi} + 2j\omega \frac{\mu_0 \ln \frac{2S}{D_0}}{2\pi} \qquad \text{(eq. 6-5)}$$

where D_0 is the loop wire diameter

The current, I_c, induced in the loop is equal to:

$$I_c = I_g \frac{j\omega M_{gc}}{2R_c + j\omega M_c} \qquad \text{(eq. 6-6)}$$

For example, assume a steel pipe with a relative permeability of 200, an outside diameter of 1½ inch and a wall thickness of ¼ inch, a loop with a return at P=10 feet, and a loop return wire diameter D_0 equal to ½ inch. The mutual inductance is 8.5 μH/m, corresponding to a reactance at 60 Hz of 3.2 Ω/m. The inductance of the loop is 10.5 μH/m. The loop impedance at 60 Hz is 0.5 + j4.0 Ω/m. The current, I_c, induced in the loop has a magnitude equal to80 % of the ground current and a phase angle of 7 degrees referenced to the ground current. The net current inside the steel conduit is 22% of the ground current, thus providing a shielding factor of 0.22.

An iron pipe around a high-current single conductor cable may cause excessive heating due to hysteresis losses caused by the variable magnetic flux in the material of the pipe. However, net currents of a few amperes or, occasionally, a few tens of amperes are routinely carried inside steel conduits. In the application illustrated in this Section, the net current inside the pipe would be significantly reduced (to less than 1 A), which would produce flux densities less than 1 gauss in the material and, therefore, negligible heating.

6.8 Special Distribution Line Magnetic Field Reduction Techniques

A number of unconventional techniques for reducing magnetic field of distribution lines are described in the following. While the technical feasibility of these technique has been proven, they may not be as cost effective as some of the more traditional techniques described in Sections 6.2 and 6.3. Nevertheless, it is useful to consider a wide range of options, because some of these may result to be the best solution for a specific situation.

6.8.1 Field Reduction Using Cancellation Loops

One of the most attractive techniques for the reduction of magnetic field of transmission lines is the application of "cancellation loops", so named because the current circulating in these loops create a magnetic field which partially cancels the previously existing field. Several utility applications have been designed. Although commercial installations are limited, analytical techniques, experimental verification, and pilot projects were sufficiently advanced to warrant publication of the EPRI handbook: "Magnetic Field Management for Overhead Transmission Lines: Field Reduction Using Cancellation Loops" [8].

The concept of cancellation loops is applicable also to distribution lines. Potential applications are described in the EPRI handbook [8]. There are several considerations that make cancellation loops less attractive for distribution lines than for transmission lines, such as:

- There could be other more cost effective options to reduce field exposure from distribution lines
- Distribution line currents cannot be assumed balanced and symmetric
- The possible presence of a current carrying neutral complicates the design of cancellation loops
- The net current of distribution lines cannot be easily compensated by cancellation loops

6.8.2 Split Phase Design

This design is applicable to distribution lines with or without unbalance, but with little ground current (i.e. the neutral carries most of the unbalance). An example application is shown in Figure 6-9. The split phase configuration has two wires for each phase, placed so that the center of each pair of wires coincides with the location of the neutral.

The field at one meter above ground was calculated for an average phase current of 300 A and for three different situations: (1) balanced phase currents, no neutral current, no ground current, (2) 30 % unbalance, but no ground current (255 A, 390 A, 255 A in the phases, 135 A in the neutral), and (3) 30% unbalance and 20% ground current ratio (255 A, 390 A, 255 A in the phases, 108 A in the neutral, 27 A net current). The results of the calculations for the split phase and for the traditional configuration are shown in Figure 6-10.

The split phase magnetic field is significantly lower than that of a traditional configuration when there is no net current, i.e. when all the unbalanced current, no matter its value, returns in the neutral. The field reduction caused by the split phase design becomes larger as the distance from the line increases. For instance, the largest field underneath the line at one meter above ground is 7.8 - 8.7 mG (depending on the degree of unbalance) for the traditional configuration and 2.3 - 2.5 mG for the split phase configuration. At 100 feet from the line, the split phase field is 0.3 mG as compared to the 2.2 to 2.5 mG for the traditional configuration.

The presence of a net current, however, eliminates the advantage of the split phase configuration. In fact, for the split phase configuration the net current gives by far the most important contribution to the magnetic field at all distances. The use of split phase configurations is advantageous only when all the unbalanced current returns in the neutral.

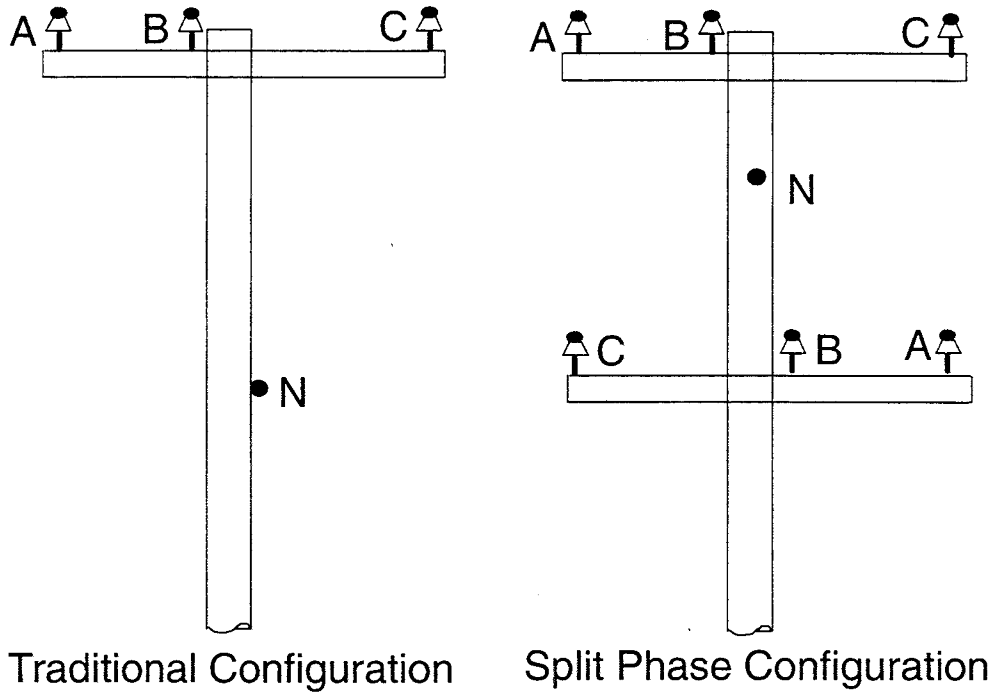

Figure 6-9 Split phase configuration compared with traditional cross arm configuration

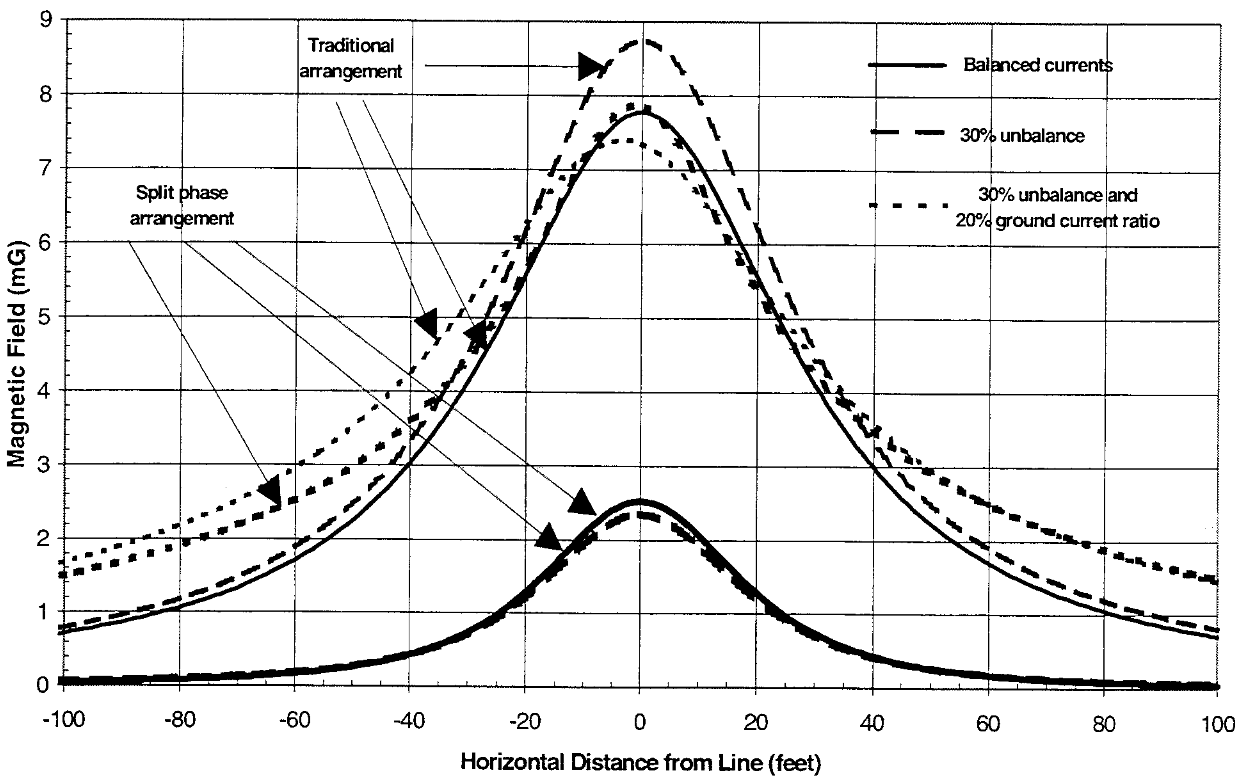

Figure 6-10 Magnetic field profile of a split-phase distribution line, with and without unbalance and ground current (comparison with traditional configuration)

6.8.3 Optimization of Phases of Multiple Circuit Distribution Lines

If more than one major feeder is strung on the same poles, and if each circuit is relatively well balanced, there is an optimum combination of phases of the three circuits that achieves the lowest possible magnetic field. This optimum can be determined by exercising field calculation software, such as RESICALC (see Appendix A), for the most likely values of line currents and for different combination of phasing. The example of Figure 6-11 illustrates three different feeders on the same pole and two different combinations of phasing, the common arrangement with the same phasing for all the three circuits and the arrangement that gives the lowest field for the combination of currents shown in the figure. The calculated lateral profiles for the two different phasing combinations is shown in Figure 6-12. The magnetic field depends on the unbalance and on the angles between phase currents of each feeder. These quantities generally vary with time. Calculations must be made for different scenarios to determine the configuration that is most likely to give the lowest overall field.

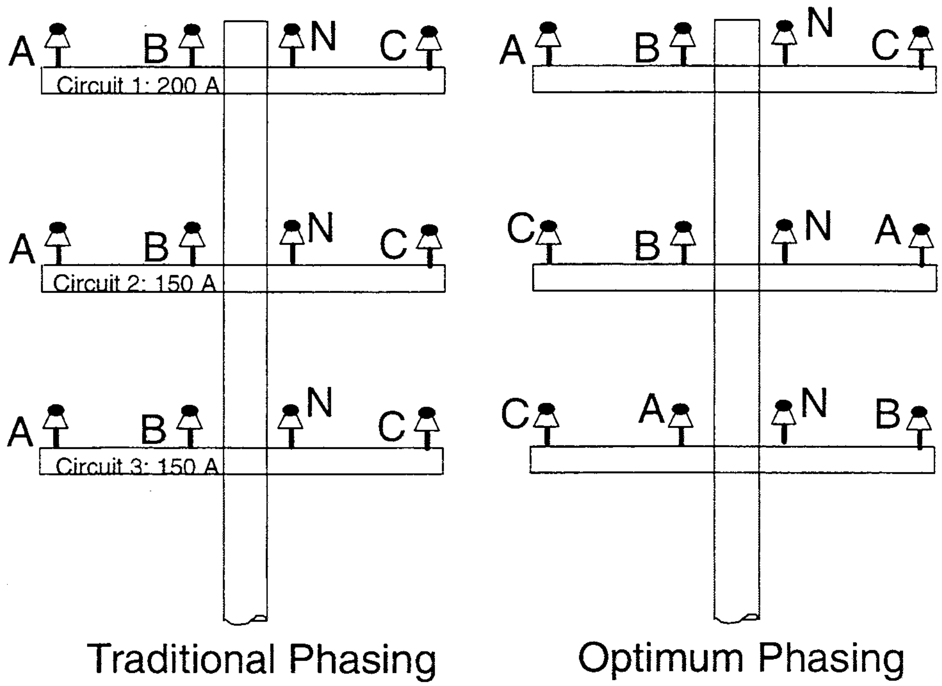

Figure 6-11 Different phasing combinations for multiple distribution feeders strung on the same pole

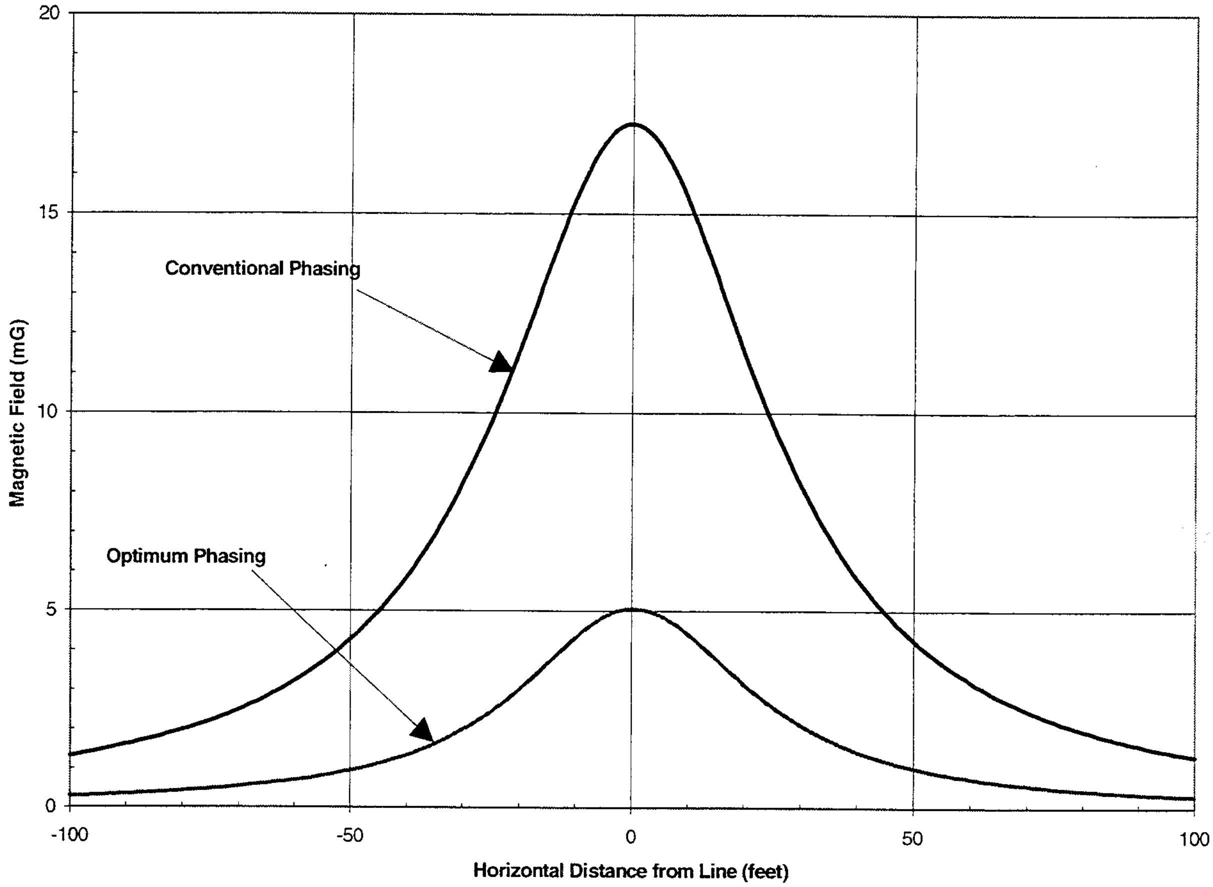

Figure 6-12 Lateral magnetic field profiles for multiple distribution lines (see Figure 6-11)

6.8.4 Shielding of Adjacent Buildings

A technique to reduce exposure from distribution line magnetic field consists of shielding the subject rather than modifying the line. This may be the case when it is not clear which line modification, if any, is effective to reduce magnetic field. It may be desirable, for instance, to shield a building from the external magnetic field, be that from a distribution or a transmission line or any other source.

Techniques for shielding are described in the EPRI's "Magnetic Field Shielding Handbook" [9]. Shielding may be accomplished using sheets of high permeability materials, or of high conductivity materials, or a combination of both. Shielding can also be accomplished using loops of conductive wires or bars as described in the EPRI Cancellation Loop Handbook [8].

6.9 Reduction of Magnetic Field from Underground Distribution Lines

Underground distribution lines cause negligible fields when the loads are balanced or unbalanced with no net current. Even heavily loaded (e.g. 100 A) three phase distribution lines without net current produce fields of only a few milligauss directly above the cable; the field rapidly decays with increasing distance from the cable. However, balanced load conditions are a rare occurrence. Quite often underground distribution, both single and three phase primary lines, have a significant amount of net current which may cause elevated fields in sidewalks and residences near the cables.

Magnetic field reduction techniques for the reduction of net currents described in Section 6.3.2, 6.4, and 6.5 apply also to underground distribution.

Net currents are caused by the neutral connections to water pipes, telephone and cable TV shields, and the earth. Another common reason for the presence of net currents in underground single phase primary lines is the looping of a feeder and bonding of the feeder neutrals, as shown schematically in Figure 6-13. A looped feed may have a net current even without any ground current. This occurs because the current of each distribution transformer is provided by the primary phase conductor from a well defined direction, while the return current may flow in both directions of the neutral. As a result, for instance, in section 1 of the feeder loop shown in Figure 6-14 the phase current is zero because the switch is open. However, the neutral conductor may have a current. The net current, I_{net}, in the loop is the same in all the loop sections.

A method to reduce the net current is described in [10]. The method consists of the installation of a 1:1 current transformer. The current transformer magnetically couples the phase conductor and the neutral conductor of the power cable, thereby forcing the neutral current to be equal to the phase current. The net current and the magnetic field that the net current generates would be reduced to zero. This concept can be applied to several components of the power system and is similar to the concepts described in Section 4.5 (Neutral Current Control Device) and in Section 6.7 (diversion of ground current using steel pipes).

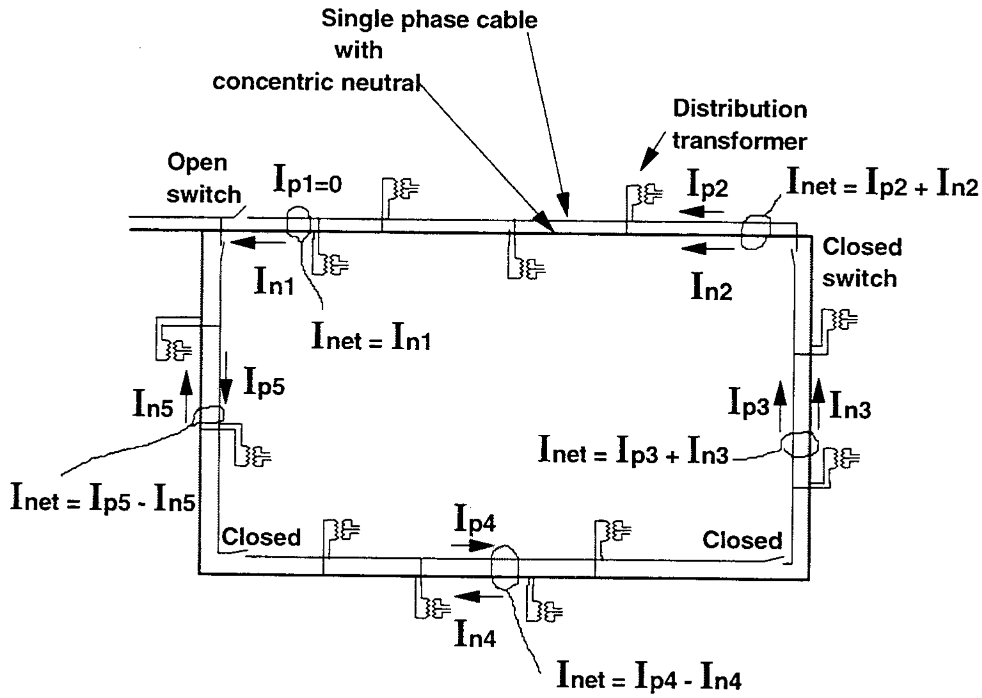

Figure 6-13 Looped single phase underground distribution feeder

For application of the current transformer method to looped underground distribution feeders, the neutral must be isolated from ground (as it is, in effect, in residential neighborhoods with plastic water lines) except for specific grounding locations. To guarantee performance the current transformer must be installed between each grounding location. The current transformer can be installed anywhere in the loop of Figure 6-12. Assuming the installation indicated in Figure 6-13, a load, I_p, would cause a neutral current, I_n, in the section indicated in the figure given by:

$$I_n = I_p \frac{jM_{p1} - Z_2 + jkX_t}{Z_1 + Z_2 + jX_t} \quad \text{(eq. 6-7)}$$

where M_{p1} is the mutual inductance between phase and neutral in section 1 of the loop, Z_1 is the impedance of the neutral in section 1 of the loop, Z_2 is the impedance of the neutral in section 2 of the loop, X_t is the reactance of the current transformer, and k is the coupling coefficient between the current transformer windings.

Current transformers can be constructed with a reactance of several ohms and a coupling coefficient $k \approx 1$. Since the other impedances in the circuit are generally much less than 1 ohm, the previous equation reduces to $I_n \approx I_p$

The current transformer can be designed as a unit by itself, to be spliced into a distribution primary cable, or can be integrated into a distribution transformer design.

The current transformer method has not been verified with practical installations. Pilot installations are necessary to determine the cost effectiveness of this solution, the adequacy of its performance during transient conditions (such as the sudden insertion of loads), the potential for resonance conditions, etc.

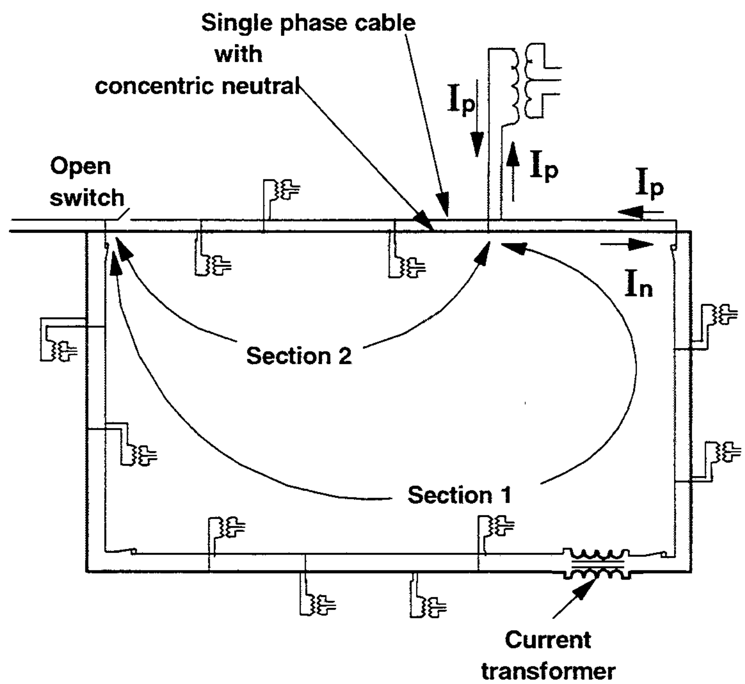

Figure 6-14 Looped single phase underground distribution feeder

6.10 Summary Distribution System Magnetic Field Management Techniques

The following table summarizes the magnetic field management techniques applicable to different components of the distribution system described in this Section.

Subject	Magnetic Field Management Technique	Reference
Overhead Three-Wire	Change existing cross-arm configurations into compact delta or spacer cable	Section 6.2.1
Primary Lines	Use armless delta or compact vertical for new constructions	Section 6.2.1
	Reduce line currents by increasing the distribution line primary voltage	Section 6.2.2
	Increase distribution line pole height	Section 6.2.3
	Use cancellation loops	Section 6.8
	Use a split-phase design	Section 6.8
	Optimize phasing of multiple circuit lines	Section 6.8
Overhead Four-Wire	Change existing cross-arm configurations into compact delta or spacer cable	Section 6.2.1
Primary Lines	Use armless delta, compact vertical, or spacer cable for new constructions	Section 6.2.1
Balanced Component	Reduce line currents by increasing the distribution line primary voltage	Section 6.2.2
	Increase distribution line pole height	Section 6.2.3
	Use cancellation loops	Section 6.8
	Use a split-phase design	Section 6.8
	Optimize phasing of multiple circuit lines	Section 6.8
Ground Component	Balance the loads of the three phases	Section 6.3.2.1
	Increase the size of the neutral	Section 6.3.2.2
	Isolate primary and secondary neutrals	Section 6.4
	Change the 4-wire into a 5-wire system	Section 6.5

Secondary and Service Drops		
<u>Overhead</u>	Use triplex rather than open wire configurations	Section 6.6
<u>Underground</u>	No change in existing practices	
Residential Grounding System	Place distribution transformers at the center of the services	Section 4.5
	Locate and repair broken or bad service neutrals	Section 4.5
	Place dielectric inserts in metallic water lines	Section 4.5
	Insert a Net Current Control Device on the service drop	Section 4.5
	Use triplex rather than open wire secondary and service drops	Section 4.5
	Place water line and electric service entrances at the same location of the residence	Section 4.5
	Divert ground current path using steel conduits around the grounding system and a conductive loop	Section 6.7
Underground Distribution Primary Lines	Use special current transformer in looped single phase primary feeders	Section 6.9

Reducing the magnetic field produced by the distribution system is a complex matter. The distribution system of today is the result of several decades of evolutionary changes that had as primary objectives the safety, reliability, and cost effectiveness of the system. For this reason, wholesale changes in the design and construction practices of the distribution system to reduce magnetic field may not be practicable given the persisting uncertainty regarding possible health effects of the magnetic field. Nevertheless, it may be practicable for new overhead line construction to use arrangements that result in a low magnetic field produced by the balanced field component. The ground component of the magnetic field is the most difficult to reduce. Although many techniques have been proposed, they have not been extensively tested and verified in different service conditions.

6.11 References

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9. "Handbook of Shielding Principles for Power System Magnetic Fields", Vol. 1: "Introduction and Applications", EPRI TR-103630, April 1994.

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A

RESICALC

A.1 RESICALC Overview

RESICALC is a magnetic field modeling program running under Microsoft Windows™ version 3.1 or higher. It models the power-frequency magnetic fields from a user-specified array of transmission lines, distribution lines, and custom conductors. The resulting magnetic field environment can be presented in a variety of graphical formats including contour and three-dimensional maps. The RESICALC software uses Power Line Calculator (WINPLC) for Windows, an application that calculates several important power line parameters including the symmetrical current components for multi-phase electrical circuits. Further information on Power Line Calculator can be obtained by consulting the Power Line Calculator for Windows User Manual or EPRI Report
TR-101408.

RESICALC is very similar to its companion program, SUBCALC. Whereas, SUBCALC's purpose is to model the magnetic field in and around a substation, RESICALC's primary purpose is to model the magnetic field in and around a residence or within a neighborhood. Both programs can model the magnetic field from overhead transmission and distribution lines as well as user defined conductors. RESICALC's features include:

- The full Graphical User Interface (GUI) provided through the Windows environment.
- Modeling of magnetic fields from any arbitrary array of power lines and grounding conductors through its icon and menu driven interface. The mouse quickly and easily establishes the location of lines and conductors in the model area. The modeling feature supports a wide variety of common transmission and distribution line configurations, common grounding conductor configurations, and allows customized conductor configurations.
- A data base supporting user-specified transmission and distribution line, and grounding conductor configurations for easy retrieval and application.
- High quality profile, contour and three-dimensional maps representing the calculated magnetic fields.
- Standard statistical analysis of the calculated magnetic fields.
- Full editing capabilities allowing the modification and storage of existing models.

- The RESICALC software includes Power Line Calculator (PLC), a Windows application that calculates the symmetrical current components, power factor, apparent power and reactive power for arbitrary multi-phase power lines. Further information of Power Line Calculator can be obtained by consulting the Power Line Calculator for Windows User Manual or EPRI Report TR-101408.

A.2 Magnetic Field Source Modeling in RESICALC, Version 2.0

Overhead transmission and distribution lines, residential secondary and grounding system conductors, such as service drops and water pipes, and underground lines can be modeled in RESICALC, Version 2.0. These sources can be significant contributors to the magnetic field.

A.2.1 Overhead Transmission Lines

Modeling overhead transmission lines requires the user to "draw" the transmission line and specify the phase and overhead shield wire currents. The transmission line does not have to be connected to a substation for the program to perform properly. Because currents on most transmission lines are well balanced in phase and magnitude, usually there is usually little or no error introduced by assuming a balanced condition. For very lightly loaded lines, radial lines, lines serving individual industrial customers, or other non-typical situations, the user may want to measure the transmission line currents (both magnitude and phase angle) to provide accurate inputs to the program.

A.2.2 Overhead Distribution Lines

The method used for modeling overhead transmission lines is also used for modeling overhead distribution lines. The magnetic field contribution of distribution lines is likely to be very important for predicting the magnetic fields near a residence since conductors are lower to the ground, conductor currents may be large, and net currents and ground currents may exist.

Unlike transmission line currents, distribution line currents will frequently be unbalanced in both magnitude and phase angle. Typically, the vector sum of the phase currents and neutral current will not equal zero because some current will flow on paths other than the electric neutral (e.g., on pipes, utility grounds, and in the earth). For the model to provide accurate estimates of the magnetic field, all input values must be accurately determined or estimated. If balanced phase current magnitudes and angles are used, inaccuracies in the calculated magnetic field in areas near the distribution lines could result.

A.2.3 Secondary and Grounding System

The secondary distribution system and the residential grounding system can contribute significantly to the magnetic fields in a residence. The net current for a residence could contribute to the magnetic fields in a neighbor's house, depending on the path and magnitude of the net current. RESICALC 2.0 contains algorithms for determining both the path and magnitude of the net current in a secondary grounding system. The user must draw the geometry for the system (secondary, service drop, service entrance, service panel, water pipes, water main) and RESICALC will compute the currents on the grounding conductors.

A.2.4 Underground Lines

Underground transmission and distribution cables can be modeled using the existing tools. At this time, this is a crude, but workable, method for modeling cables. If the user knows the location of the cables, magnitude and angle of phase currents and neutral currents, and the split of the return current between the neutral and the other (earth) return paths, underground circuits can be successfully modeled using this version. Like overhead distribution lines, the imbalance may be substantial. Simple assumptions for input values may introduce large errors near the underground circuit. However if the cables are closely spaced, the area of inaccuracy will likely be less than that for overhead circuits.

A.3 RESICALC Features

The following list summarizes major RESICALC features.

- RESICALC can model any arbitrary array of overhead Transmission and Distribution lines, and residential secondary and grounding system conductors such as Service Drops and Water Pipes, through an icon driven interface. A mouse is used to establish the location of lines and conductors in the model area.
- A Database of Transmission Lines, Distribution Lines, and Custom Conductors, supports conductor configurations which can be customized to your specifications.
- The magnetic field can be represented by a Profile Plot, Contour Map, or 3-Dimensional Map.
- The magnetic field can be described using standard Statistics.
- A number of options are available for Printing the RESICALC maps. You can print a map with a title and a subtitle.
- Full Editing capabilities allow the modification of existing models.
- Models can be stored and retrieved from disk files for later study and modification (see Files in the Reference).
- With an accessory program called the Power Line Calculator for Windows, you can calculate important power line parameters including Symmetrical Current Components for modeling unbalanced current situations.

B

EPRI'S MAGNETIC FIELD RESEARCH FACILITY

B.1 Introduction

A Magnetic Field Research Facility (MFRF) was constructed at EPRI's Power Delivery Center in Lenox, Massachusetts (PDCL) for the purpose of reproducing power system magnetic fields under controlled conditions. The facility includes a 1200' overhead distribution line that can be configured in different ways and a water distribution system that can be connected in different ways to the neutral wires. The distribution line serves a two-story test residence and 18 other residences simulated by load cabinets. The electrical connections, grounding, electrical wiring, and appliances of the test residences were designed to study the effect of source parameters on residential magnetic fields.

Because electricity is so widely used in our daily lives, sources of magnetic fields in the home are many and varied. In addition to utility power lines, residential magnetic field sources include home wiring, home water pipes (which partially return neutral currents to the utility transformer), electric appliances, and heater wires in floors and ceilings. However, much uncertainty exists as to the characteristics of magnetic fields in homes.

The MFRF enables the researcher to produce magnetic fields from various sources under controlled conditions. The facility simulates a small segment of a residential neighborhood, including an overhead distribution line with distribution transformers and load points, each representing a house, a water pipe system for grounding, and a basic house shell with typical wiring and grounding arrangements. These elements can be easily reconfigured to produce the wide variety of currents and magnetic fields typically found in residential neighborhoods. For example, most overhead distribution lines can be simulated, whether wye or delta systems. Grounding arrangements for line and load points can be changed, neutral and ground circuit impedances can be adjusted, and the water main parallel to the line can be connected to or insulated from the load grounding system. Moreover, each residential service can be grounded to a water pipe or by means of a ground rod, and distribution line currents can be controlled using a variable terminal load.

The primary purpose of the MFRF is the study of magnetic field sources, in particular the dependence of magnetic fields on the source parameters. The MFRF has also been found valuable for other purposes: development of magnetic field instrumentation and measuring techniques, development of protocols and training of crews for residential magnetic field measurements, demonstrations, seminars, and magnetic field measurement workshops. The facility is also a valuable tool available to EPRI member companies for the study of field reduction methods.

A transmission line model test area is available for the study of transmission line fields. An underground primary distribution line is available for the study of magnetic field produced by underground distribution lines.

B.2 Description of the Magnetic Field Research Facility

A schematic plan view of the MFPF is shown in Figure B-1. The overhead distribution line is 1200 (360m) long with a 90 degree angle along its length. It serves 18 simulated residences, a test residence, and a terminal load.

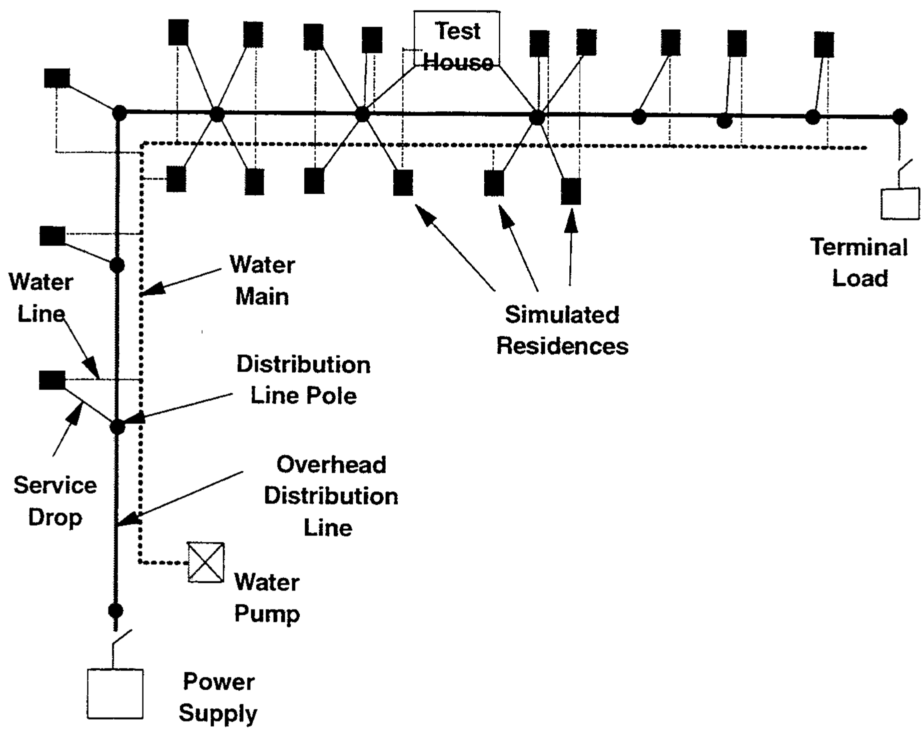

Figure B-1 Schematic plan view of EPRI's Magnetic Field Research Facility

The line is strung with three primary conductors insulated for 23kV phase-to-phase, a neutral, and secondary wires. The primary wires are arranged horizontally with an average spacing of 44.5 inches (1.13m), and the neutral, which is common to the secondary, is below the primary wires at a distance of 66 inches (1.68m). The height of the primary wires above ground at the crossarms is approximately 28.5 feet (8.7m).

The secondary wires are twisted around the neutral. The details of the wire arrangements are shown in Figure B-2.

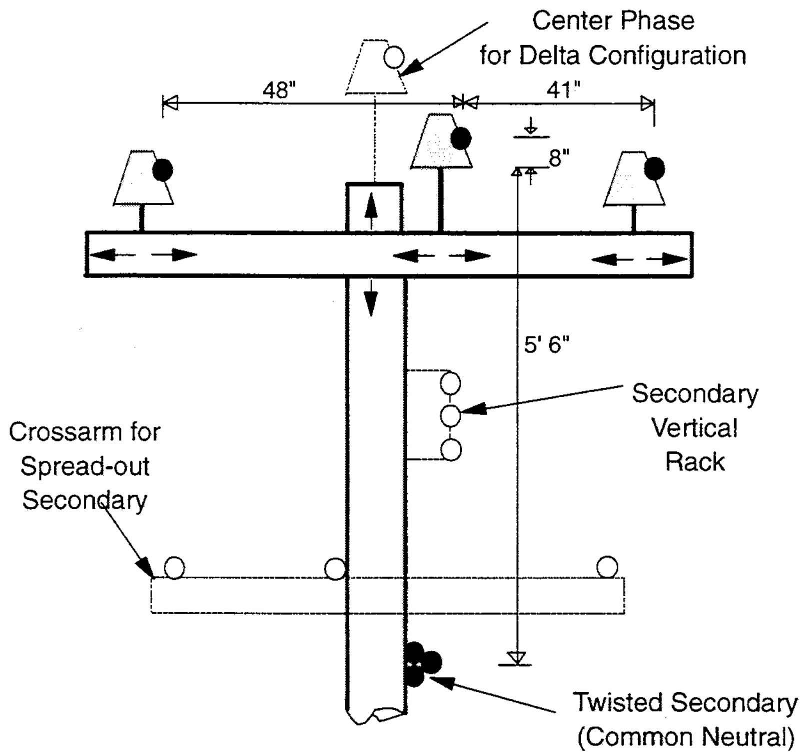

Figure B-2 Details of the overhead distribution line wire arrangement. Dashed lines are additional elements required for different configurations

Provisions have been made to change the geometry, if desired. The primary crossarm can be moved down the pole, the two lateral primary wires can be moved along the crossarm. The center primary wire can be moved atop a pole extension to form a delta configuration, the secondary wires can be spread horizontally on an additional crossarm or vertically on a secondary rack and, finally, a separate neutral can be provided for primary and secondary.

As configured, the line can be used for all or part of its length to simulate a variety of overhead distribution lines. This is achieved by energizing some or all of the wires, as follows:

1. Secondary wires only.
2. Single phase primary with neutral, with and without secondary.
3. Two-phase primary without neutral, with and without secondary.

4. Three-phase primary without neutral, with and without secondary.
5. Three-phase primary with neutral, with and without secondary.

B.2.1 Power Supply

The overhead primary distribution line can be energized with different voltages using different arrangements of the power supply transformers. With the arrangement shown in Figure B-3 (both 3x50 kVA bank and 3xl0 kVA bank with Y-Y connection), the primary can be energized with a line-to-line voltage of 4160 V (2400 V line-to-ground when switch S2 is closed and switches S3 and S4 are open) or with a line-to-line voltage of 480V (277V line-to-ground) when switch S2 is open and switches S3 and S4 are closed.

If the 3x50 kVA bank is connected Y-Δ, the primary can be energized with a line-to-line voltage of 2400 V. when S2 is closed and S3 and S4 are open. This connection is used for tests with two-phase or three-phase primary, without neutral, and distribution transformers connected between phases.

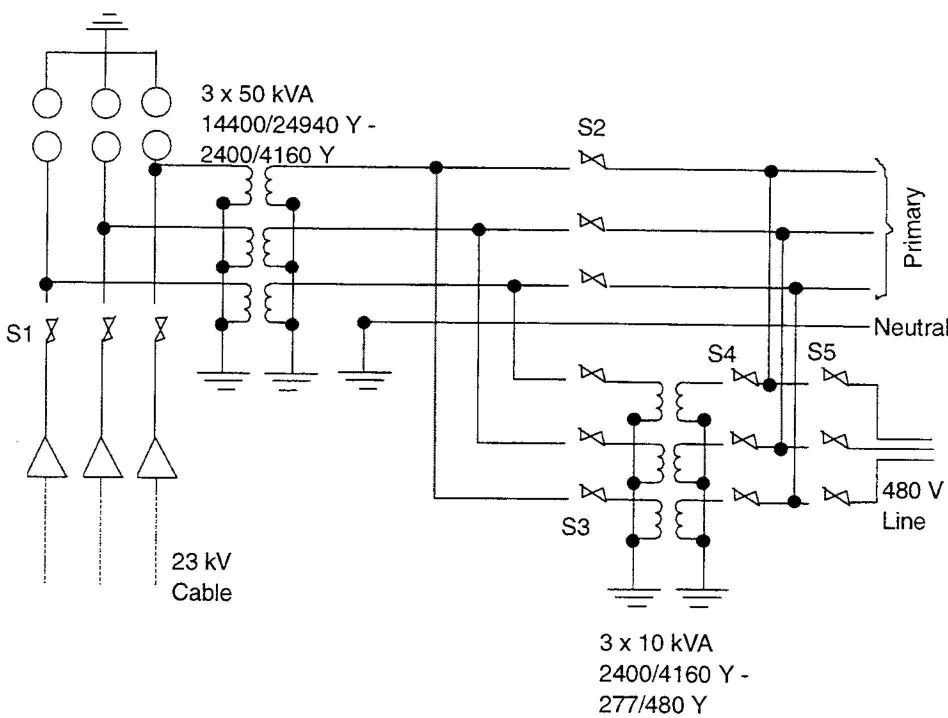

Figure B-3 Schematic of the Magnetic Field Research Facility distribution power supply

B.2.2 Simulated Residential Services

The secondary can be interrupted at every pole, so that it can be configured to serve different combinations of residences from any distribution transformer that can be either alone or banked with others. Distribution transformers are provided at nine poles along the distribution line. Each transformer has two primary bushings so that the primary can be connected either phase-to-ground or phase-to-phase. A cut-out fuse is provided for each transformer. The transformers are rated 2400V-120/240V, 25kVA.

The neutral can also be interrupted at every pole. This allows simulation of different lengths of secondary sections when the primary is used without a neutral. Impedances can be inserted in series with the neutral to study their effect on neutral return currents and related magnetic fields.

Each simulated residential service consists of a stub pole with a load and grounding panel. The service drop is attached to the top of the stub pole. The electrical connections at a simulated residential service are shown schematically in Figure B-4. The two 120V wires and the neutral of the service drop arrive at a panel where it is possible to (1) insert an impedance in series with the neutral or interrupt the neutral altogether, (2) connect the neutral to a ground rod directly or through an impedance, (3) connect the neutral to a copper water line directly or through an impedance, and (4) connect loads through a receptacle. The copper water line is interrupted by a plastic insert. A #8 copper wire is attached to the water line at both sides of the plastic insert to allow measurements of the electric currents in the water line and also to simulate the situation in which the water line connection from the residence to the water main is not entirely metallic.

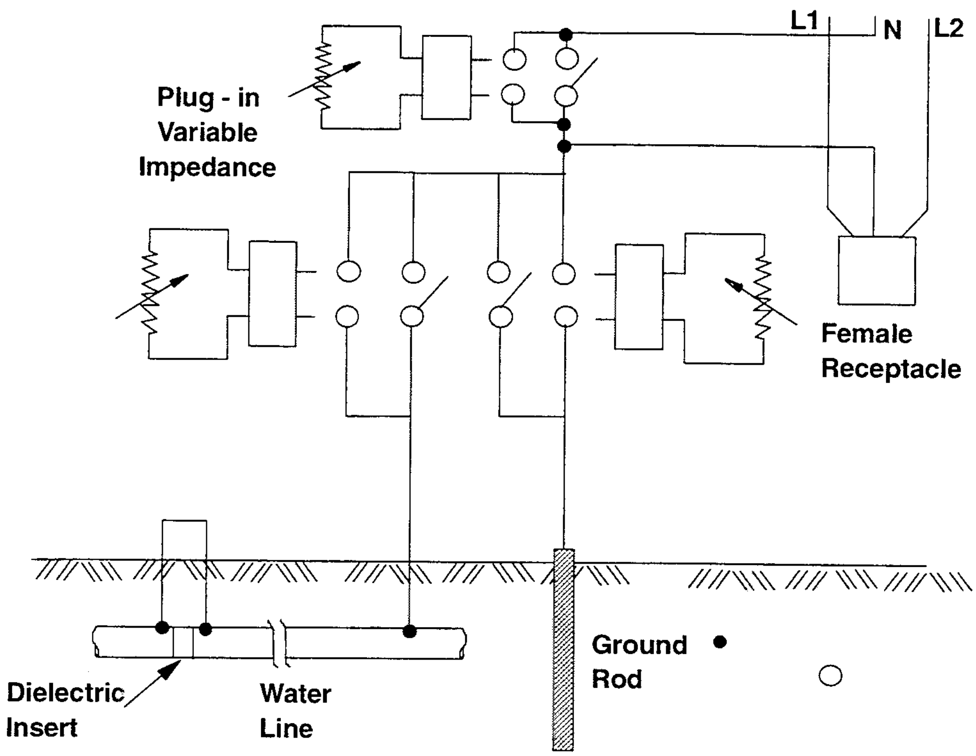

Figure B-4 Electric connections at a simulated residential service

Residential load units are available to simulate residential loads at up to two locations simultaneously. A load unit consists of eight 0.8 kW-120V and six 1.1 kW - 240V resistive heating elements, connected through individual circuit breakers and a main breaker to a power cord for insertion at a simulate residence's load and grounding panel. In addition, several receptacles are available on the load unit for household appliances, if desired.

B.2.3 Water Distribution System

The MFRF is equipped with a water distribution system. A water main runs parallel to the distribution line for its entire length at a distance of approximately 28 feet (8.5m) from the distribution line. Another section (see Figure B-1) runs perpendicular to the distribution line. A pump, housed in a small shed, is used to maintain water pressure in the water main and service lines.

The water main is a pipe of ductile iron with thickness of about 3/8 inch (1 cm) and an inner diameter of 8.25 inches (21 cm). The outside surface has a coal tar coating. The pipe is in 20 feet (6 m) sections inserted into each other with the help to bronze wedges. The pipe is buried at a depth of about 5 feet (1.5 m). Every three sections, i.e. every 60 feet (18 m), plastic slip joints are intentionally placed to interrupt the electrical continuity of the pipe. Conductors (#2 copper wire) are welded to the pipe on both sides of each joint and are brought to the surface so that pipe current can be measured and impedances inserted, if desired. A copper water line connects a point near each simulated residence to the water main in a straight path perpendicular to the main. The water line of each residence is then electrically connected (using a bare #6 copper wire clamped to the water line) to the service entrance point through a switch or an impedance (see Figure B-4).

B.2.4 Terminal Load

The overhead distribution line can supply power to a terminal load. The purpose of this load is to cause primary currents to flow so that the resulting magnetic fields can be accurately measured. Using the residential load units at full load, primary currents of about 5A per phase can be obtained. In order to produce larger currents without the use of larger loads, the line voltage is reduced to 480V, as previously discussed, and a 480V terminal load is inserted at the end of the distribution line. This terminal load consists of fifteen 1.2kW resistive heating elements that can be inserted up to five per phase.

Currents of up to about 20A in each primary phase can be caused by insertion of the terminal load. The neutral of the terminal load can be connected to the neutral of the primary or to the water main at the end of the line or to both, in order to produce varying degrees of net current. Unbalances between phases can be produced by applying different loads to different phases.

B.3 Description of Test Residence

A two-story house with approximate dimensions 40 feet x 26 feet (12 m x 7.8 m) and with full basement was built near the overhead distribution line at the center of one span as shown in the plan view of Figure B-1. The distance between the external wall of the test residence and the center of the distribution line is 16 feet (4.9 m). The house has a heating system (baseboard hot water by oil), a bathroom, a septic system, and running water provided by means of plastic pipe from the town water main, some 500 feet (150 m) away. The interior is kept open to the maximum extent possible. All construction are non-conductive materials (wood, fiberglass insulation, asphalt shingles).

The test residence has a variety of electrical wires and can be connected to the distribution line of the MFRF in a variety of ways that will be described in the next section. When the test residence cannot be powered from the test line, for instance during line maintenance or test setups, it is possible to receive power from the local utility from a single phase distribution line approximately 250 feet (75 m) away. The service pole is located about 100 feet (30 m) from the test residence and the service neutral is grounded to a ground rod there. Power is metered at this location, and a three-way switch can disconnect the live wires and neutral of the service. With this service disconnected, and the MFRF de-energized, the 60Hz ac magnetic field at the test residence is less than 0.1 mG.

The purpose of the test residence is to study the characteristics of magnetic field sources inside the residence and the interaction between the residence and external sources. Based on the experience gained during EPRI's previous pilot study on residential magnetic fields a number of magnetic field sources were identified. These include:

- Service drop and grounding system
- Appliances
- Subpanel with grounded neutral or accidental grounding of the neutral
- Improperly wired multiple-way switches
- Loops formed by grounding wires and water pipes
- Knob and tube wiring
- Radiant heat wires (ceiling or floor)

All of these sources can be duplicated in the test residence.

B.3.1 Service Drops and Grounding Connections

Particular attention was given to service drop and grounding systems because these have proven to be common sources of residential magnetic fields. Six different service drop paths (Sl to S6) are available in the test residence, as indicated in Figure B-5. Three service drops come from one pole and three from another; two are underground and four overhead; the overhead service drops reach either the closest or the furthest corner of the house from their poles.

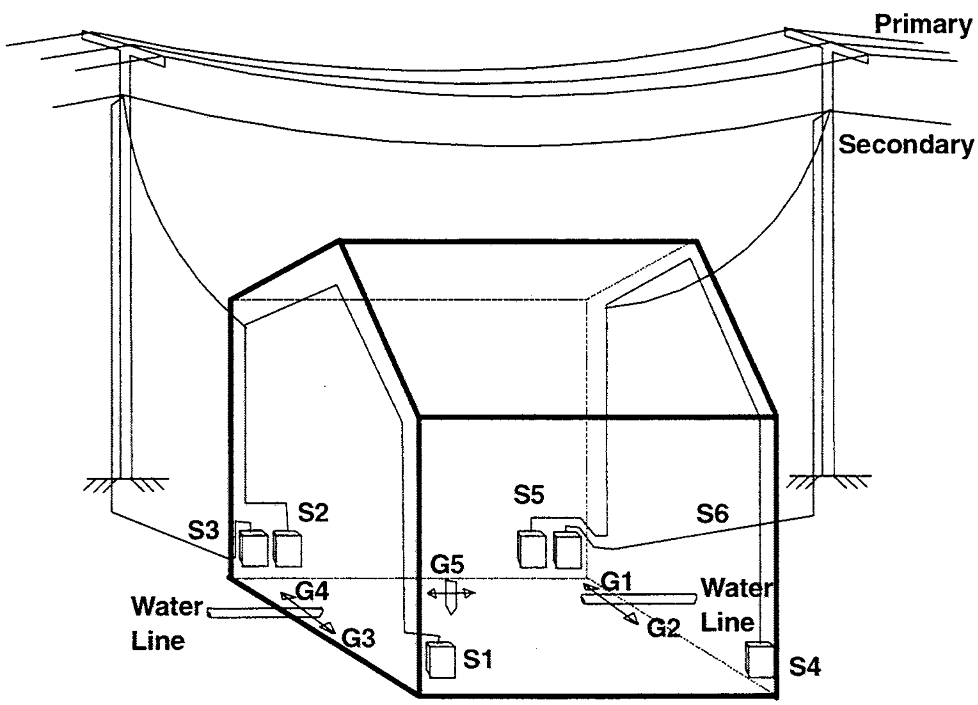

Figure B-5 Service drops and grounding systems of the test residence

There are five grounding paths, (Gl to G5); two each to the water pipes on opposite sides of the test residence and one to a ground rod. Neutral connections of the service drop to each water line can be made both along the shortest or the longest route along the periphery of the basement ceiling.

Power to the residence can be supplied from each of the six service entrances, but only one at a time, via a connection from the residence electrical panel to one of six ports. The choice of the ground connection can be controlled from the ground switch panel. The MFRF also has a cabinet containing a double throw switch used to power the test residence either from the MFRF or from the local utility.

B.4 Uses of the Magnetic Field Research Facility

The MFRF is capable of reproducing the sources of residential magnetic fields. This facility has a variety of uses responding to current needs of utilities. These uses include:

- Seminars designed to demonstrate the magnetic field characteristics of various sources. Seminars are addressed to utility executives, utility engineers, public relations personnel, and people involved in the regulatory process.

- Magnetic Field Measurement Workshops for utility engineers and training of crews for residential field measurements. The flexibility of the facility and the large variety of sources that can be simulated render these workshops very effective.
- Testing of measuring techniques and testing of instrumentation. Magnetic fields of different spatial, temporal, polarization, and harmonic characteristics can be produced to test techniques and instrumentation under a large variety of conditions.
- Studies of field sources, determination of the effect of source parameters. It is possible to simulate a utility's particular situation, to evaluate the magnetic field produced, and to determine the effect of design changes.
- Evaluation of the efficiency of methods of field reduction or management that may be proposed.
- Study of the magnetic field characteristics of appliances and office equipment.
- Study of water pipe currents caused by the power system.

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